Jarðvísindastofnun Háskólans RH-05-2023

Tephra dammed lakes in the Veidivötn area, Iceland: 2000 years of lake evolution within a volcanic system.

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Cover photograph: Bedded, compacted tephra, 15-20 m thick, in the flank of the largest Vatnaöldur tephra ring that dammed Tungnaá river (in foreground) in 877 CE to form the temporary, unstable lake Langalón. Photo Guðrún Larsen.

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Abstract

Unstable tephra dammed lakes are a category of ephemeral lakes that occasionally form in volcanic areas. Such situations may arise where rivers flow across and within volcanic areas where explosive eruptions are the dominant volcanic activity. Depending on their location and size such lakes may pose hazard to natural and manmade environment when the tephra dams fail.

Large unstable/temporary tephra dammed lakes formed in the channel of the major river Tungnaá following two hydroexplosive eruptions in 877 CE and 1477 CE on the SW part of Veidivötn fissure swarm, Iceland. Together with the preceeding effusive eruption these two eruptions caused major hydrological and topographical changes in the volcanic area here defined as the Veidivötn basin. This report describes five stages in the evolution of the basin during the last ~2000 years.

The first stage, **Hnausalón stage**, followed the damming of the Tungnaá river by a lava flow of the Hnausar eruption about 2000 years ago (Tjörvahraun THj), forming a stable lake in the river channel of Tungnaá and extending into the Veidivötn basin. As a result of the lake formation and the rise in ground water level the two following eruptions in this area were explosive, tephra producing eruptions.

The second stage, **Langalón stage**, evolved following the explosive Vatnaöldur eruption in 877 CE. The volcanic fissure opened up along the edge of the Hnausalón lake, building tephra craters that formed a new and higher dam across the Tungnaá river. Consequently a ~140 km^2 lake, holding a dischargeable volume of up to 1.5 km^3, formed behind a barrier of compacted tephra. Apparently the lake level never became stable and Langalón may have emptied in one event when the tephra dam failed with an estimated maximum discharge of 10.000-20.000 m^3/s.

The third stage, **Fiskivötn stage**, followed the emtying of Langalón and was stable for about 600 years. Partial reconstruction indicates that several lakes separated by wet sediments remained in the Veidivötn basin, none larger than 10 km^2. The rivers Tungnaá and Jökulgilskvísl eroded a new channel across the SW part of the basin during this stage.

The fourt stage, **Kýlingalón stage**, followed the explosive Veidivötn eruption in 1477 CE. The volcanic fissure opened along the middle of the Veidivötn basin, damming the Tungnaá river by building tephra crater rows across its channel. Two temporary lakes formed in the river channel, the larger covering about 35 km^2 with a dischargeable volume of 0.3 km^3. Other two temporary lakes formed farther NE in the basin. The lakes emptied in several steps as the tephra dams eroded.

A new stable stage, the present **Veidivötn stage**, developed when the emptying of all the temporary lakes was completed. The Tungnaá and Jökulgilsá rivers gradually filled and levelled the crater bowls in the channel across the Veidivötn basin. The present lake configurations and topography have remained stable for more than 500 years featuring two generations of lakes, remnants of the pre-1477 CE lakes and a younger generation of lakes within the 1477 CE crater formations.

A future eruption fissure on the SW part of the Veidivötn fissure swarm will probably cut across the Tungnaá river. An eruption within the Veidivötn basin is likely to have significant explosive component and the landforms around the vents are likely to be tephra rings/cones. Topographical changes have minimized the volumes held in unstable/temporary lakes and mitigation should be possible.

The longest lasting effects of such eruption could, however, be the recovery of the ground water reservoir of this area, as a consequence of depletion of water through explosive interaction with magma, topographic changes and reorganization of the lake system.

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Definition of tephra.

Tephra is used herein as a collective term for all clastic material emitted from a volcanic vent, regardless of size and type. This includes juvenile material such as pumice, scoria, spatter, ash and crystals, regardless of state of consolidation, and nonjuvenile material from the substrata of the volcanic vent such as fragments of older lava and hyaloclastite, gravel and sand.

A tephra dam can, for example, be a crater rim or a thick deposit of unconsolidated/consolidated pumice, scoria, ash and lava fragments; a crater rim of pumice and ash loaded with gravel, sand and silt from underlying strata; a slide from a failed crater flank consisting of partly fused/consolidated spatter, scoria and ash.

Terms referring to clast size are bombs >6.4 cm, lapilli 6.4-0.2 cm and ash <0.2 cm. The terms pyroclastic material, pyroclasts, are synonymous with tephra although not used here.

1. Introduction

The effects of external water on erupting basaltic magma have been dealt with from many points of view, covering all environments from glaciated areas to shallow lakes and high ground water to deep ocean (e.g. Thorarinsson 1965; Walker and Croasdale 1971; Wohlets and Sheridan 1983; White and Houghton 2000; Houghton et al. 2004; Jude-Eaton et al. 2012 and references therein). The effects of subglacial eruptions on small glaciers and a major ice cap, as well as the hazards involved, have received due attention lately (e.g Gudmundsson et al. 1997, 2012).

Relatively little attention has, however, been focused on how volcanism affects the ground water and surface water reservoirs within volcanic areas. The most obvious effects are damming or diversion of waterways, e.g. by accumulation of volcanic products or by volcano-tectonic movements. Such changes are normally small but in countries like Iceland, where major glacial rivers flow across or within the volcanic areas and along the prevailing fissure swarms, the effects can be both extensive and hazardous (e.g. Larsen 1984; Hákonardóttir 2019).

As a result of a volcanic eruption, the hydrological conditions may either be permanently altered and lead to a new stable situation, or temporarily changed into an unstable and possibly hazardous situation. Tephra dammed lakes are a category of ephemeral lakes which may be the most dangerous water bodies that form in volcanic areas outside ice caps. This paper describes temporary and permanent tephra dammed lakes formed in two subsequent eruptions on the Veidivötn fissure swarm (Fig.1), in 877 CE and 1477 CE as well as the evolution of the Veidivötn lake area for the last 2000 years. In that particular area the volcanism-induced hydrological changes resulted in a change of eruptive style within the volcanic province, from predominantly effusive (Hnausar eruption) to predominantly explosive (Vatnaöldur, Veidivötn) eruptions (Larsen 1984, Larsen et al. 2013).

A large glacial river, Tungnaá, crosses the southwestern part of the Veidivötn fissure swarm. Tungnaá river is presently the source of a substantial portion of the country's hydropower production, with two large hydropower plants and reservoirs lying in its course and contributing water to three other hydropower plants in southern Iceland. Its course has been affected by all eruptions on the southwestern part of the fissure swarm. In the eruptions of 877 CE and 1477 CE Tungnaá was temporarily dammed by tephra craters and their associated deposits.

2. Geological setting - The Veidivötn Fissure Swarm

The Bárdarbunga-Veidivötn volcanic system lies mostly within the Eastern Volcanic Zone (EVZ, Fig. 1a, inset) with the central volcano, Bárdarbunga, situated below the NW edge of the Vatnajökull ice cap (Sæmundsson 1978, 1979; Larsen 1984, Larsen et al. 2013, Gudmundsson et al. 2016). The system is about 190 km long and up to 20 km wide. The shorter arm of the volcanic system, Dyngjuháls Fissure Swarm, strikes north-northeast from the central volcano whereas the 100 km long Veidivötn Fissure Swarm (VFS) strikes southwest (Fig. 1a). A hyaloclastite massif, Gjáfjöll (Chasm Mountains) lies approximately midways on the Veidivötn Fissure Swarm and is here used as a divide between its higher lying northeastern half, partly covered by the Vatnajökull ice and the lower lying southwestern half where the Veidivötn lake area lies (Fig. 1a). The SW tip cuts through the silicic volcanics of the Torfajökull caldera.

The Holocene volcanism on the SW-part of the VFS is characterized by eruptions on long fissures, dotted with spatter cones, scoria cones and tephra rings, and surrounded by lava fields and tephra flats. Also present are hyaloclastite ridges formed during the last glaciation, rising above more eroded bedrock of hyaloclastites and pillow lavas. The topographically lowest area

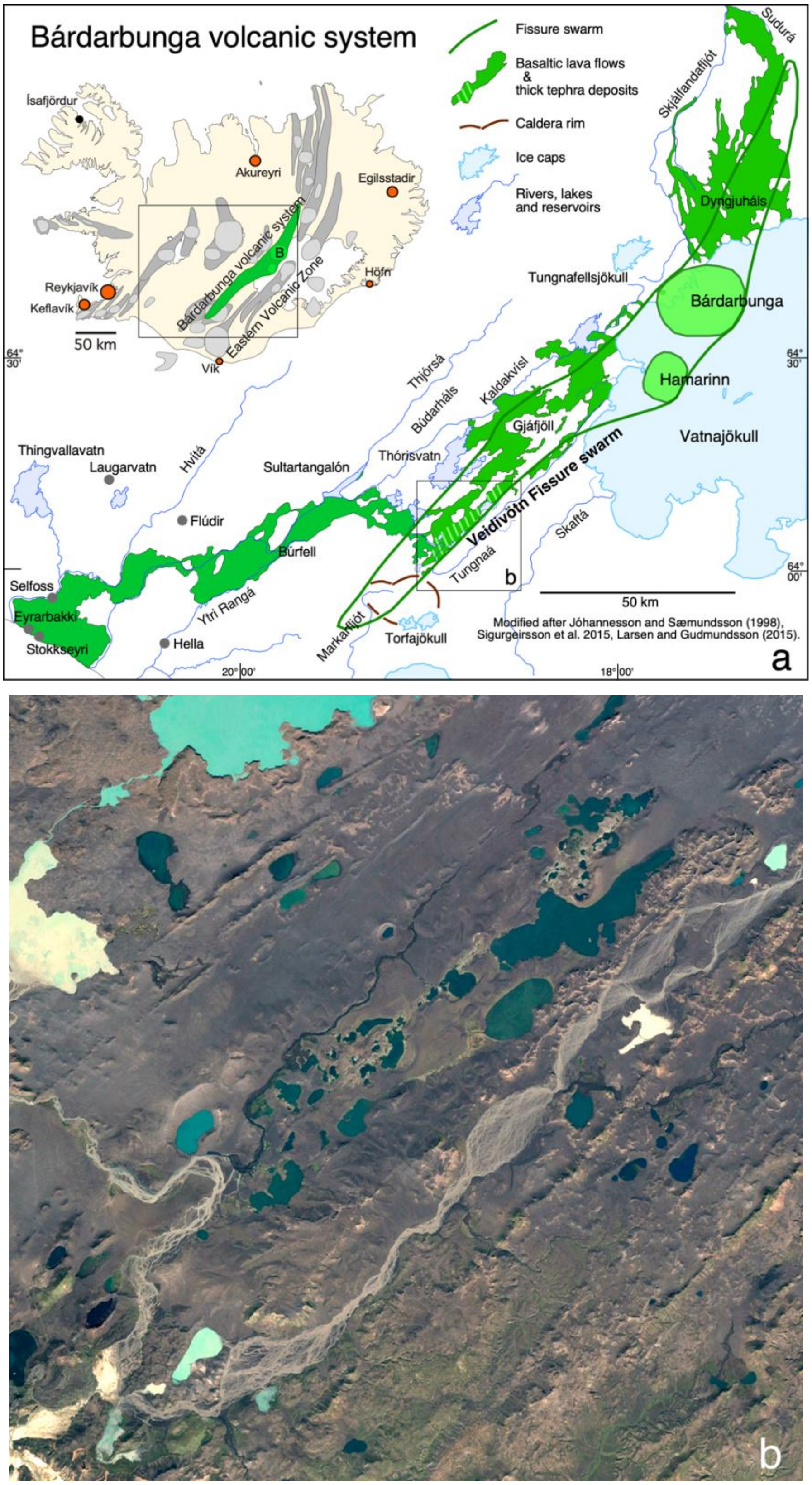

Figure 1. a) Bárdarbunga Volcanic System. Inset shows its position on the Eastern Volcanic Zone. Basaltic lava flows are shown in green, thick basaltic tephra deposits in the Veidivötn area are hatched. b) Satellite image (Google Earth) showing the Veidivötn basin with its numerous lakes and surrounding areas, characterized by SE-NW trending volcanic fissures and hyaloclastite ridges. Tungnaá river flows SE of the fissure swarm, crossing it in sharp bends. Torfajökull caldera rim in lower left corner.

is found close to the SW tip of the VFS, in the form of a SW-NE trending basin now occupied with numerous lakes (Fig. 1b, Fig. 2). A major glacial river, Tungnaá, flows along the VFS until it is diverted by the topographically higher Torfajökull area towards N across the VFS and, at the same time, through the SW part of the Veidivötn basin.

In the early Holocene, while ice was retreating from the interior, explosive volcanism apparently dominated the activity on the VFS, manifested by numerous tephra rings now surrounded by lava flows (Vilmundardóttir et al. 1988, 1990, 1999). This was soon replaced by effusive volcanism, producing some of the largest known Holocene lavas with volumes of 15-25 km^3 (Vilmundardóttir 1977, Hjartarson 1994, 2011). This change in activity was facilitated by effective drainage of surface and ground water through valleys and deep gorges cut by ice and/or meltwater. The lava flows, however, were channeled to the lowlands through these very same gorges and valleys and gradually filled them in, thereby raising the river beds and related ground water tables within the volcanically active area. In the last 2000 years a change from a well-drained terrain into an extensive lake area took place on the SW-part of the VFS. As a result, the eruptive style reverted from effusive to explosive volcanism in the last two eruptions (Larsen 1984; Larsen et al. 2013).

The effects of the last three eruptions on the hydrology of the Veidivötn basin can at least be partly reconstructed, while the effects of the previous eruptions can only be guessed at. The oldest of the three eruptions took place roughly 2000 years ago.

3. Present conditions in the Veidivötn basin - Topography, lakes, rivers

The Veidivötn basin is 30-35 km long with a maximum width of 4-5 km (Fig. 2, shaded area), flanked by a steep hyaloclastite ridge (Snjóöldufjallgardur) to the SE, and low hyaloclastite hills and the 877 CE Vatnaöldur tephra rings to the NW. The fissure of the youngest eruption, the 1477 CE Veidivötn eruption, runs along the middle of the basin with various volcanic landforms around the vents. Numerous interlocking tephra rings and cones, with crater diameter up to 2.5 km, and small spatter cones mark the trace of the fissure. Its products cover most of the basin floor, thinning away from the crater rows towards the edges of the basin which are now its lowest lying parts. Despite massive infilling by the Veidivötn volcanics, most of the basin still lies below 600 m a.s.l., in contrast to the 700-800 altitude of the Snjóöldufjallgardur mountain range to the SE and the 600-700 m a.s.l. topography to the NW, dominated by the Vatnaöldur tephra rings (Fig. 2). More detailed descriptions of these eruptions are in Ch. 5.

A group of lakes, Veidivötn, occupies the central and NE part of the basin (Fig. 2) and a few lakes are scattered towards its SW end. Stable lakes larger than 0.1 km^2 are 24-26 (Rist 1975), but the total number of lakes in the basin varies depending on changes in the local ground water table. Two generations of lakes are present. The younger generation lakes lie within and are younger than the volcanic formations associated with the 1477 CE Veidivötn eruption (Larsen 1984, Larsen et al. 2013). They are numerous but generally small ($\leq$0.85 km^2). Remnants of older generation lakes, that occupied the basin prior to the eruption, are found at the edges of the basin, including four the largest lakes (1 - 9 km^2) which are lined up along its SE edge.

Two rivers enter the SW part of the basin, the major glacial river Tungnaá, originating at the W edge of the Vatnajökull ice cap, and its tributary Jökulgilskvísl, which drains the Torfajökull caldera. The latter transports rhyolitic rock debris into the SW part of the basin. Being the major supplier of alluvial material, it deflects the larger river by building a fan into its bed. A third river, Vatnakvísl, drains the middle part of the basin and joins the Tungnaá before it leaves

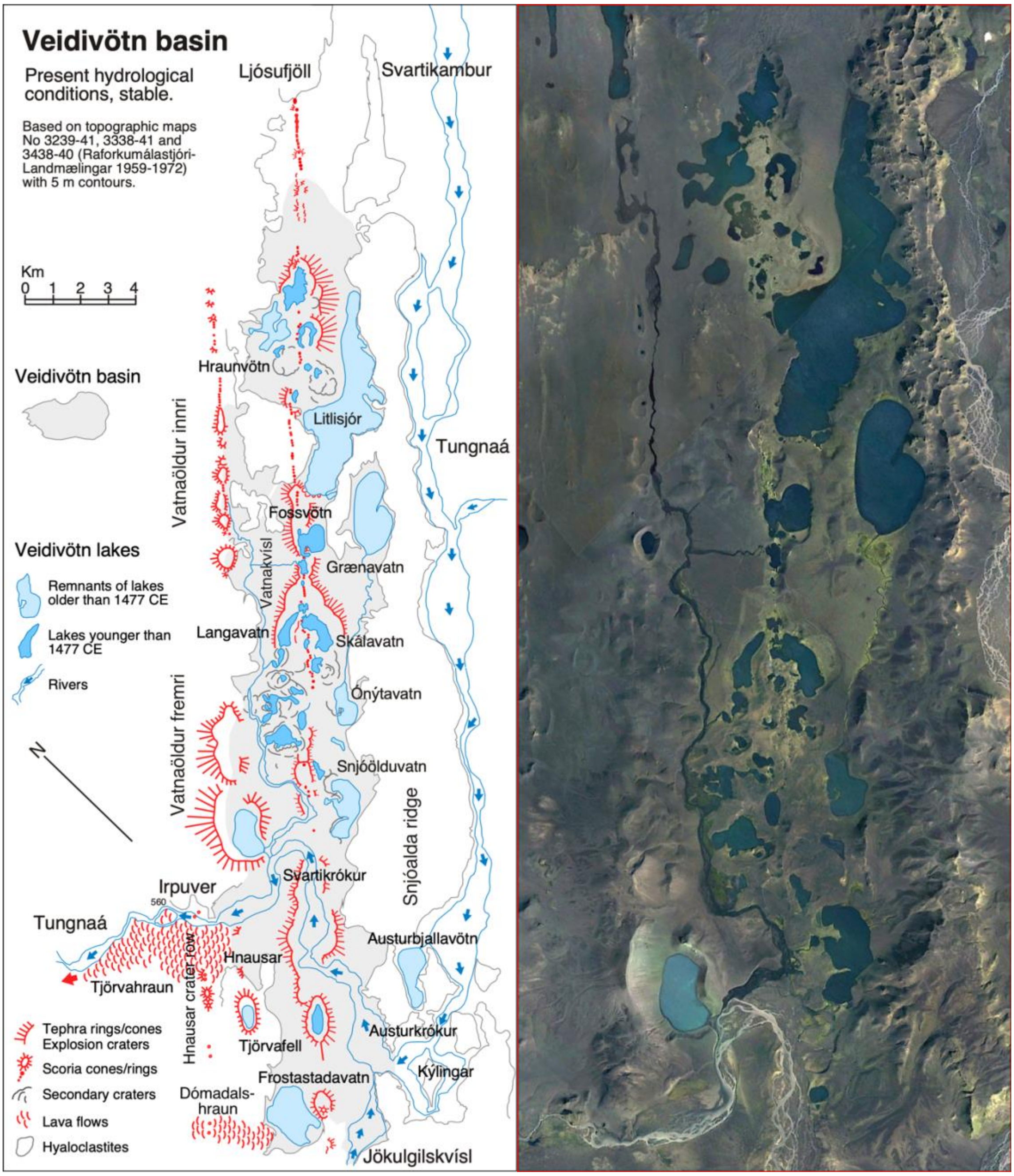

Figure 2. Present condition in the Veidivötn basin, here defined as extending from Ljósufjöll in the NE to Frostastadavatn in the SW.

Left panel: Simplified map of the Veidivötn basin (grey shading) and adjacent formations. On the SE-side the basin is flanked by the Snjóalda hyaloclastite ridge. The 2000 year old Hnausar crater row and the 877 CE Vatnaöldur crater rows lie along its NW-margin. The crater rows of the 1477 CE Veidivötn fissure are lined up along the middle of the basin. Two generations of lakes are found in the basin. Large older generation lakes (pale blue) lie along the SE margin and at the SW end. Smaller and more numerous younger generation lakes (darker blue) lie within the volcanics of the 1477 CE Veidivötn fissure. Two glacial rivers, Jökulgilskvísl and Tungnaá, enter the SW part of the basin. Surface drainage from the basin is throught a narrow pass near Irpuver.

Right panel: Satellite image from Google Earth showing details of the lakes in the central part of the basin. Note the smooth outlines of the older generation lakes, e.g. Grænavatn, as compared to those of the younger generation lakes, e.g. Skálavatn. Also note the rugged hyaloclastite ridge flanking the SE-side of the basin.

the basin near Irpuver, along a NW-SE trending depression in the hyaloclastite formations (here referred to as the Irpuver depression or Irpuver pass). Together, their current yearly discharge is 80 m^3/s on average (Jónsdóttir and Einarsson 2003). Surface drainage from the basin is controlled by a lava barrier in the riverbed of Tungnaá near Irpuver at ~560 m a.s.l.

4. Reconstruction - methods

Reconstruction of the pre-1477 CE hydrology and topography of the Veidivötn basin can only be carried out to a certain extent. It is primarily based on topographic maps in 1:20000 with 5 m contours (Raforkumálastjóri (NDE), Orkustofnun (NEA), Landsvirkjun (NPC) 1959-1985, maps 3239-41, 3338-41, 3438-40) and bathymetric maps of the lakes in the basin (Rist 1975), also with 5 m contours. The ArcticDEM maps, with 5 m contours, (IslandsDEMv1, Porter et al. 2018), the website Map.is (Loftmyndir ehf) and the new geological map of the Eastern Volcanic Zone (Kaldal et al. 2018, topography mainly based on the NDE/NEA/NPC maps) have also been consulted. These maps are used in combination with isopach maps of air fall tephra from the two youngest eruptions (Fig. 3) which represent minimum tephra thicknesses deposited in the basin, and drillhole logs through the lava flows of the third youngest eruption (Vilmundardóttir 1977) to assess topographic changes caused by the three eruptions. In this report, elevations are preferably given with 5 m intervals, as 560 m a.s.l., 565 m a.s.l. etc (cf the last paragraph).

The Holocene basin fill is partly volcanic material and partly sediments. An early Holocene effusive eruption within the basin has been suggested (Vilmundardóttir 1977) and lava lobes from eruptions outside the basin may have entered the basin locally. The substrata in the basin are partly exposed in its SW-part. Elsewhere in the basin clues about the material now buried below the volcanics come from nonjuvenile material ripped from the substrata by the explosive activity and deposited in the crater rims and proximal tephra deposits.

Alluvial and lacustrine sediments that accumulated in the SW part of the basin when the Tungnaá river was temporarily dammed are exposed in several localities in the now downcut bed of the river. They consist mostly of subrounded to rounded rhyolitic gravel and sand which are also found in the tephra of some crater walls in this area. Non-juvenile material found in crater rims elsewhere in the basin are fragments of phyric and aphyric basaltic lava, fragments of hyaloclastite and clots of laminated lacustrine sediments. Many of the crater rims in the central part of the basin are low and deformed by subsidence or by secondary explosions, implying that the substrata was soft and water-logged. Rims loaded with fragments of basaltic lava as well as rims with exposures of hyaloclasite or pillow lavas, are generally higher than those with gravel or lacustrine sediment. This allows certain assumptions to be made about the substrata in the various parts of the basin, and the topography below the craters rims as well.

Shorelines left by temporary higher lake levels in the basin are found in several places. Those discernible on aerial photographs were projected onto topographic maps. Accessible shorelines were inspected in the field for relationship to tephra deposits of the two youngest eruptions.

Information is scant on ground deformation in major rifting episodes on the SW part of the Veidivötn Fissure Swarm. Maximum throw on faults in a 3200 year old lava near Gjáfjöll (Vilmundardóttir et al. 1990) is about 30 m but this may be the result of more than one episode. At the SW end of the Veidivötn basin, the surface expressions of tensional tectonics are fading out (Jóhannesson and Sæmundsson 1998) as the tectonics of the Torfajökull caldera become dominant (e.g. Sæmundsson 1972). Tilting, on a local or a regional scale, may have occurred in

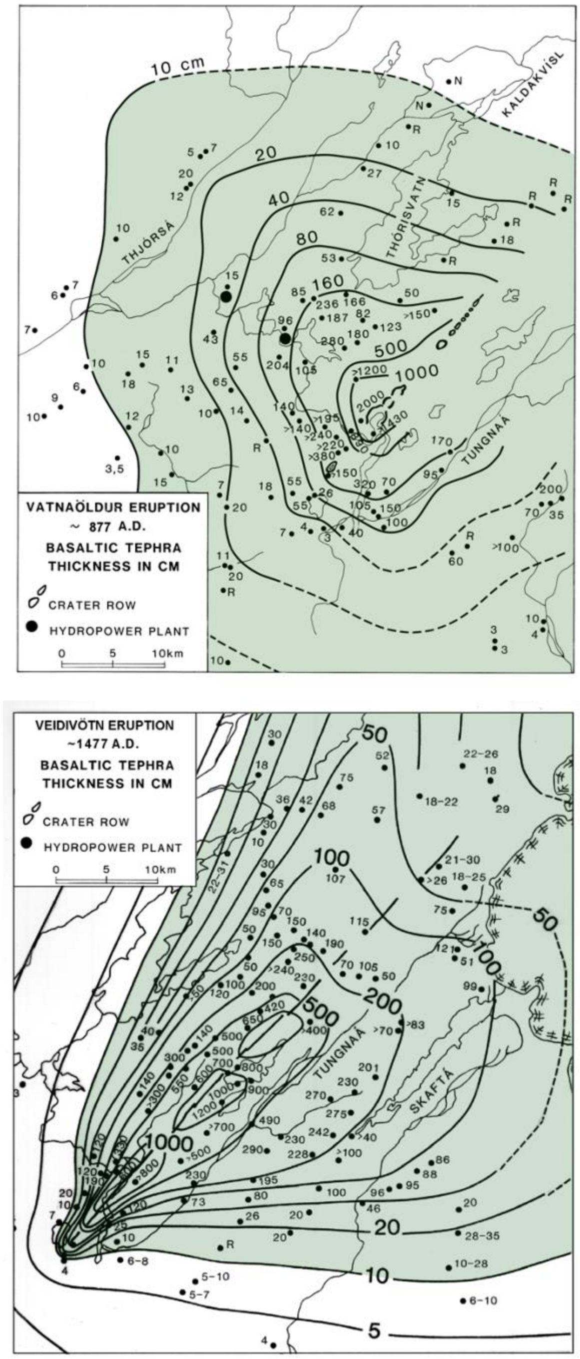

Figure 3. Isopach maps showing the proximal deposits of the Vatnaöldur 877 CE and Veidivötn 1477 CE (modified from Larsen 1984). Area within 10 cm thickness is shaded.

this area during rifting episodes but neither the magnitude nor the spatial extent is known. Post-eruption subsidence resulting from tectonic movements, post-eruption compaction or cooling contraction, is not known. Ground deformation is therefore not included in the reconstruction.

Given the unknowns and uncertainties listed above the following attempt to reconstruction should be seen as just that: an attempt to evaluate and describe changes in the hydrology of the Veidivötn basin in the last ~2000 years. The maps of the former lakes and lake systems are intended to provide insight into past conditions but are not intended to show detailed configurations or exact extent of the ephemeral lakes.

5. 2000 years of lake evolution within the VVS

The present drainage pattern of the Veidivötn basin began to develop after the Hnausar eruption about 2000 years ago (5.1) which produced the lava flows Tjörvahraun (THj, Vilmundardóttir 1977), Younger-Dómadalshraun (Sæmundsson 1972; Blake 1984; Larsen 1984) and the Hnausar crater row (Fig. 4). The Hnausar fissure lies downstream from the basin and the lava flow, THj, together with the ~3200 year old THi lava flow (Vilmundardóttir et al. 1988), still control the outflow from the basin.

The conditions prior to the Hnausar effusive eruption cannot be reconstructed with any confidence, but most of the older lava flows followed former courses of the Tungnaá river (Kjartansson 1961; Vilmundardóttir, 1977), causing gradual raising of its bed and consequent rise in ground water level in this general area.

The evolution of the lake system since the Hnausar damming has not been analysed before, but Kjartanson (1961) demonstrated that a lake had formed in the riverbed of Tungnaá as a consequence of these effusive eruptions and their lava flows, and that the lake level had been temporarily raised as a consequence of later explosive eruptions, as evidenced by shorelines. He named this lake Langalón. He did not consider the possibility that a lake had formed in the Veidivötn basin as well. Later research has revealed that a large part of this "lake system" occupied the Veidivötn basin (Larsen 1984) and that its history can be divided into several stages (this study). Here, the name Langalón will be restricted to its maximum extension.

The 2000 year history of the lake system can be divided into five stages:

1) *Hnausalón stage*, a stable stage beginning shortly (years/decades) after the Hnausar effusive eruption ~2000 years ago.
2) *Langalón stage*, an unstable stage following the Vatnaöldur explosive eruption ~877 CE.
3) *Fiskivötn stage*, a stable stage between the Vatnaöldur and Veidivötn explosive eruptions ~1477 CE.
4) *Kýlingalón stage*, an unstable stage immediately after the Veidivötn explosive eruption.
5) *Veidivötn stage*, the present stable stage.

The three eruptions causing changes in the Veidivötn basin in the last 2000 years will also be briefly described.

5.1 The Hnausar eruption and Tjörvahraun THj

The Hnausar eruption took place on a >8 km long NE-SW trending fissure (Blake 1984, Larsen 1984) that extended across the Irpuver depression and the Tungnaá river a few km downstream from the basin. The contemporary Dómadalshraun eruption did not affect the Tungnaá river. Only basalt was erupted on the Hnausar part of the fissure and the landforms at the vents are scoria and spatter cones. The ensuing lava flow, Tjörvahraun (Vilmundardóttir 1977; Kaldal et al. 2018) permanently altered the drainage from the basin by changing the topography at the Irpuver depression (Fig. 4) through which the surface water, including Tungnaá, was channeled towards lower areas in the NW (Kjartansson 1961). The main lobe of Tjörvahraun (~1 km^3) flowed towards NW and covers >70 km^2. A small lobe of the lava flow extended towards the SW part of the basin but disappears below tephra deposits from the two younger eruptions. Large blocks of the lava, found in the ejecta of two craters from the youngest eruption, indicate its presence below that part of the crater row. Presumably the lava flowed towards a low point in the basin, but its extension is not known. Kaldal et al. (2018) place the lava margin at a graben fault formed in the 877 CE eruption.

The highest part of the lava „dam“ lay upstream from where the Tungnaá flows across the Hnausar fissure (at Hófsvad ford) because a shallow graben formed along the fissure. The thickness of the lava at the dam is not known, but a thickness of 19 m was obtained in a borehole 2.7 km farther downstream (Vilmundardóttir 1977). The original elevation of the now somewhat eroded lava dam is not known with certainty but must have been some m higher than the present 560 m a.s.l.

5.2 The Hnausalón stage

Water level in the basin probably rose more than 20 m as a consequence of the Hnausar eruption, forming a stable lake(s), Hnausalón (Fig. 4). At present, the bed of the Tungnaá river lies at ~560 m a.s.l. at Irpuver, cutting in a narrow channel past the now heavily scoured (and eroded) edge of the lava flow that previously banked against the hyaloclastite hills. Before being eroded by the large floods associated with the two later eruptions (see 5.4 and 5.7) the lava surface was certainly some m higher. As explained below, an outflow at ~565 m a.s.l. during the Hnausalón stage is considered realistic.

The greatest part of the area submerged during the Hnausalón stage is now covered by craters of the two younger eruptions, but the bathymetry of the basin is still discernible in a few places. The bowls of four older generation Veidivötn lakes that are lined up along the SE margin of the basin, Snjóölduvatn, Ónýtavatn, Grænavatn and Litlisjór (Fig. 2, also traced on Fig. 4), reach down to ca 544, 551, 565 and 571 m a.s.l., respectively (Rist 1975). Assuming that the lake bowls have only been affected by airfall tephra from the two younger eruptions (Fig. 3), 10-15 m thick tephra sheets should now cover their "Hnausalón bottom". At a lake level of 565 m a.s.l. the water depth in the Snjóölduvatn bowl and Litlisjór bowl would then have been 30-35 m and 5-10 m, respectively. Similarily, a removal of 10-15 m of the present tephra deposits along the NW margin of the basin would create depressions with bottoms at 545-550 m a.s.l. and water depth of 15-20 m. The reconstructed bowls are dark blue on Fig. 4.

The bathymetry along the middle part of the basin, below the 1477 CE craters, cannot be reconstructed, but their low relief and water level/depth of the nested lakes indicates a pre-eruption surface at ≤560 m a.s.l. It is likely that the bowls/depressions were interconnected and that a single large lake (pale blue area on Fig. 4) occupied the basin at this stage. The tephra thickness used to define the borders of the lake is a minimum value that does not include accumulation of wind and water eroded tephra.

Terrace of rhyolitic gravel is exposed along a 0.4 km stretch of the NW bank of Tungnaá. About 4 m above the present riverbed of Tungnaá, at ~570 m a.s.l. (Δ 570 on Fig. 4, Fig. 5), the gravel is overlain by tephra from the 877 CE Vatnaöldur eruption, which terminated the Hnausalón stage. The gravel surface has a gentle slope, if any. This gravel deposit must be a remnant of an alluvial flat or fan that formed during the Hnausalón stage (indicated by dark blue dots on Fig. 4) and was deposited in the SW part of the basin by the Jökulgilkvísl and Tungnaá rivers during that stage. As it does today, the Jökulgilskvísl river carried rhyolitic rock debris into Tungnaá at their confluence, forming alluvial flats of rhyolitic gravel.

No such deposits are exposed above the present riverbed downstream from there, despite cleancut sections 1.5 km downstream, indicating a steeper slope of the alluvium in that area (Δ 565 on Fig. 5). Such change of slope would be expected if the Hnausalón lake extended this far southwestwards and a delta was being built into it by Jökulgilskvísl and Tungnaá.

Alluvial terrace 4 m above the present alluvium/riverbed indicates either 1) a lava “dam” 4-5 m higher than the present riverbed at Irpuver, or 2) tectonic movements that changed the relative

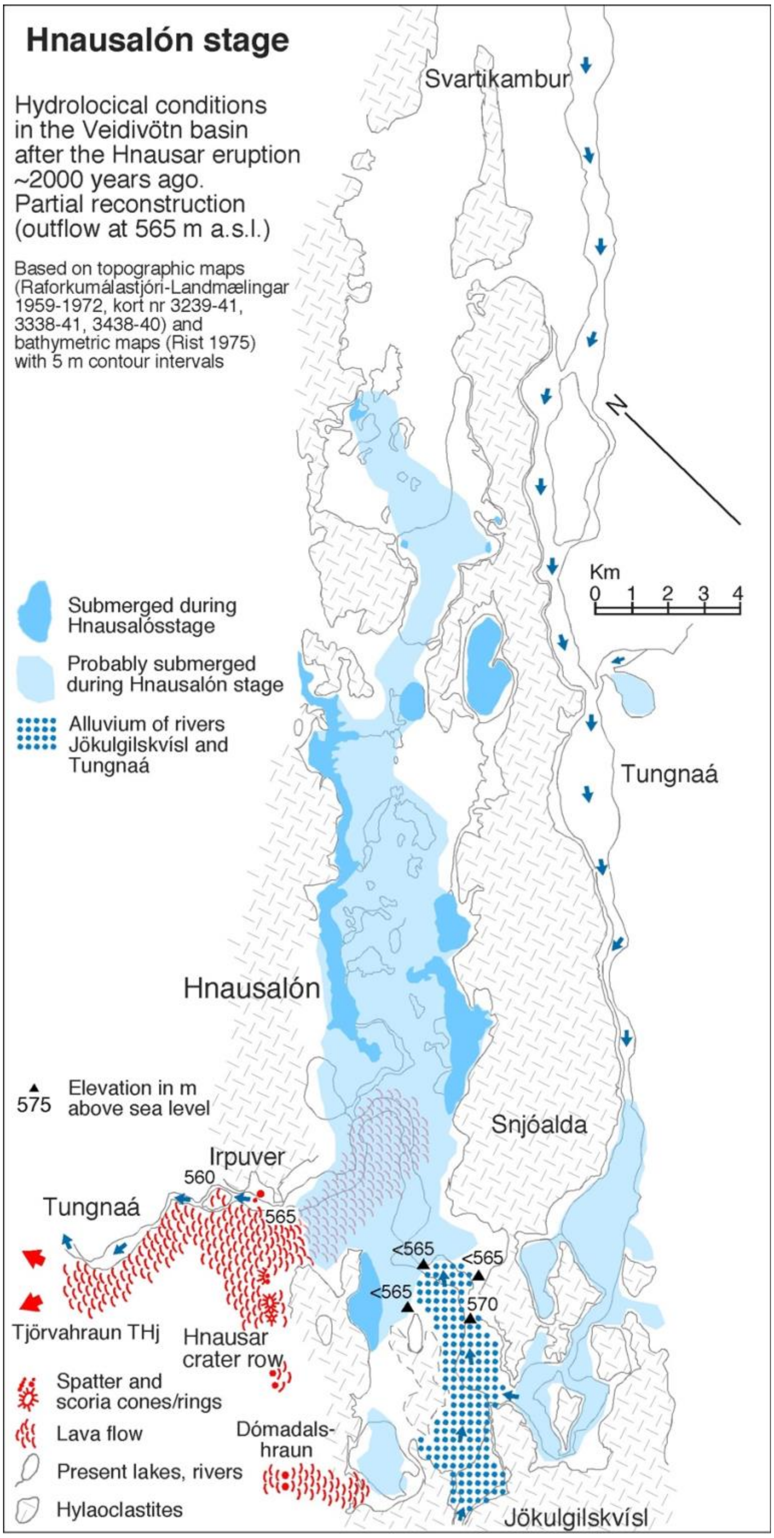

Figure 4. Hydrological condition in the Veidivötn basin during the Hnausalón stage, ca. 2000 to 1100 years ago. Tjörvahraun lava flow controls the drainage from the basin at 565 masl. Lake level ≥565. Red: Hnausar crater row and Tjörvahraun lava (basaltic), also shown is Dómadalshraun (silicic). Dark blue: areas below 565 m a.s.l. after removing 10-15 m of the present tephra cover from lake bowls in the basin. Pale blue: other areas likely to have been below 565 m a.s.l, including those currently occupied by tephra rings, and parts of the Tungnaá river bed when 5 m of tephra have been removed. Dark blue dots indicate alluvium and black triangles with numbers indicate elevation (see Appendix Fig. 1-1 for enlarged SW part of basin). The extent of Tjörvahraun THj is based on field observations, including identification of lava blocks (Vilmundardóttir pers. com.) in the ejecta of the 1477 CE Veidivötn eruption.

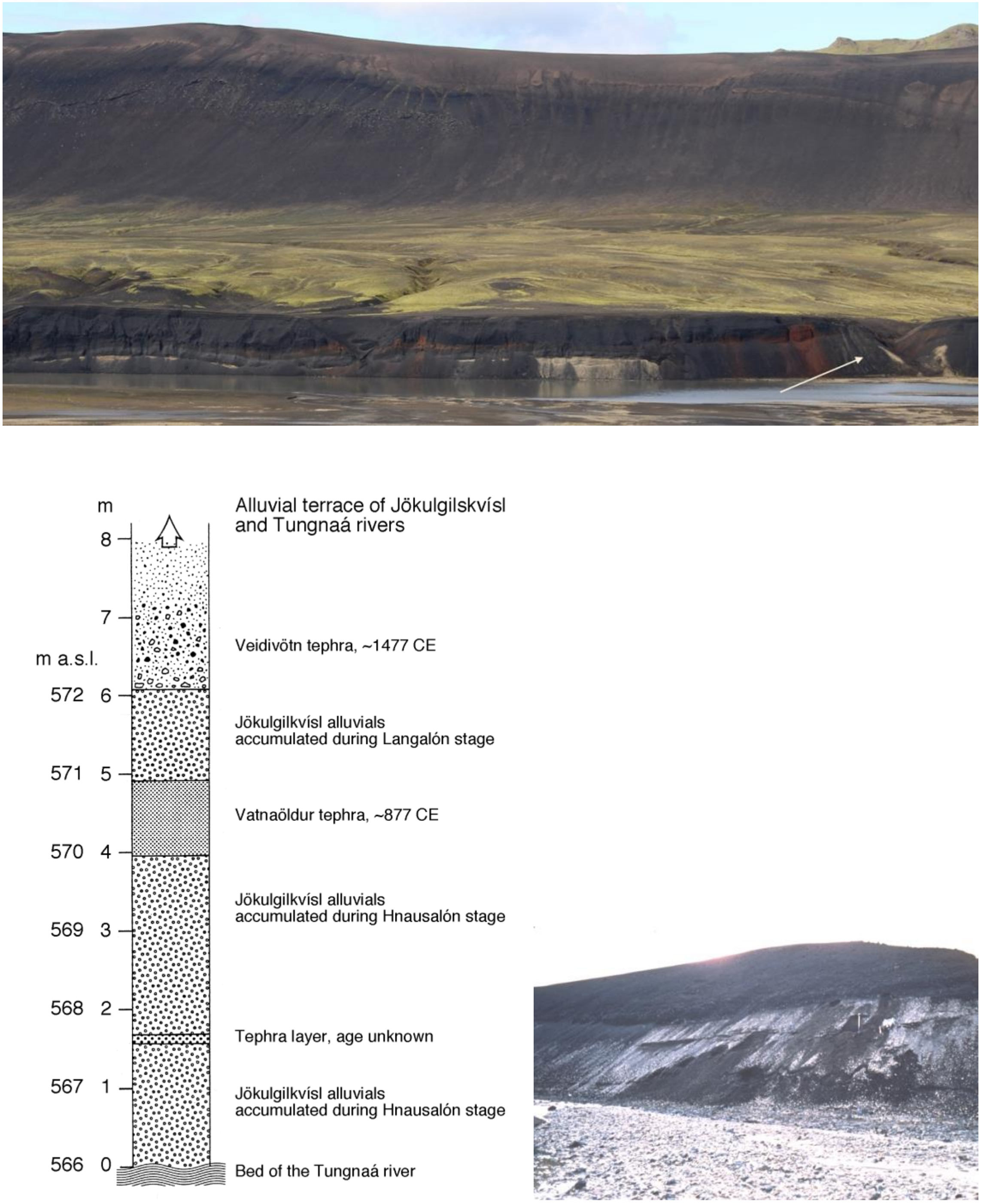

Figure 5. Top: Photograph showing an alluvial terrace of pale/beige rhyolitic gravel from the Hnausalón stage buried below a tephra slide from the SE flank of the 1477 CE Ljótipollur explosion crater, downstream from the confluence of the rivers Jökulgilskvísl and Tungnaá (photo taken 2017, see also Appendix, Figs.1-1 and 1-6). A section through the terrace (arrow), currently covered by a scree, is shown on a drawing and on the black & white photo (taken in 1982), 1 m shovel for scale. The gravel (large dots) was deposited by the Jökulgilskvísl river. Tephra from the 877 CE Vatnaöldur eruption separates the alluvium into gravel deposited during the Hnausalón stage (up to ~570 masl) and gravel from Langalón stage (up to ~572 masl). Location on Fig. 4 (black triangle 570). See also Fig. 8 (black triangle 572). NB: Conditions along this bank change as the river course shifts (meanders) and during spring floods.

heights of the two areas. The water-scoured lava surface supports the first possibility. Tectonic movements occurred along the eruption fissures (graben formations, see 5.1) to the west of the terrace, but their effects at the alluvial flats are not known.

Upstream from the confluence of Jökulgilskvísl and Tungnaá the water level may have been controlled by the alluvial fan during the late stages of Hnausalón at ≥570 m a.s.l. resulting in interconnected lakes in the Tungnaá river bed.

The area of the Hnausalón lake, ca 70 km^2 at 565 m a.s.l. as drawn on Fig. 4 (all the lakes ca 90 km^2), may be a minimum value because only the airfall tephra in the basin is used in the reconstruction, and not accumulated reworked tephra. Filling time, using the spring-fed discharge of 52 m^3/s or approximately 4.5 million m^3/day (Pálmarsson 2009) was months. The volume of water cannot be calculated with confidence because the bathymetry of basin is not known in detail. However, a one metre rise - or fall - in lake level amounted to 0.07 km^3.

*5.3 Vatnaöldur eruption 877 CE**

The Vatnaöldur volcanic fissure, about 60 km long (Larsen et al. 2013, 2015) lies partly along the NW margin of the basin and cuts across the Irpuver depression about 1.5 km upstream from the Hnausar fissure. The Vatnaöldur fissure opened alongside and partly within the Hnausalón lake. The eruption was an explosive hydromagmatic eruption that produced mostly basaltic ash and pumice, close to 5 km^3 as freshly fallen (Larsen 2018). Most of the craters (shown in red on Fig. 6) are tephra rings and the largest ones, the Vatnaöldur Fremri craters, are partly built into the basin. Filling in by the crater flanks narrowed the basin locally by nearly one-third, or by 1.5-2 km. Tephra was also deposited in the basin as an airfall sheet that thinned towards its SE margin (Fig. 3, upper panel). *Recent re-evaluation of the Greenland Ice Core Chronology (Sigl et al. 2015; Schmid et al. 2017) has verified the 877 CE date of Zielinski et al. (1998) with ±1 year uncertainity.

The immediate effect of the Vatnaöldur eruption was to obstruct the flow of Tungnaá where the crater row crossed the river. Tephra deposited into Hnausalón during the early stages of the eruption and/or tectonic movements associated with the eruption may have caused overtopping of the Hnausalón lake and floods in Tungnaá before the river was fully dammed by the crater row and its deposits (Larsen 2019). At the end of the eruption, however, a tephra dam had formed that effectively contained the Tungnaá river and a new lake, Langalón, began to form.

5.4 The Langalón stage

The maximum extension of the lake system in the Veidivötn and Tungnaá basins occurred as a result of the Vatnaöldur eruption when a temporary lake, Langalón, with a possible maximum areal of 140 km^2 at 580 m a.s.l. (Larsen 1984), was formed (Fig. 6). The effects of the Vatnaöldur eruption on the lake system were both temporary and permanent, or short-term and long-term, as described in the two following sections.

Water-scoured remnants of tephra craters indicate where the Vatnaöldur crater row crossed the Irpuver depression. The "tephra dam" consisted of a row of tephra craters superimposed on the Hnausar lava and the thick tephra deposits surrounding the crater row (indicated by red triangles on Fig. 6, see also the cover photo). This area has been scoured by a flood that swept away most of the lightweight material, but primary Vatnaöldur tephra is still preserved in depressions in the Hnausar lava, below a cover of reworked tephra. Minimum height of the dam can be estimated from tephra thickness outside the flooded area, which is 9-10 m some 0.6 km downstream from the crater row. This is close to where the lava surface was at and above 565 m a.s.l., inferring that the minimum elevation of the tephra dam was at least 575 m a.s.l.

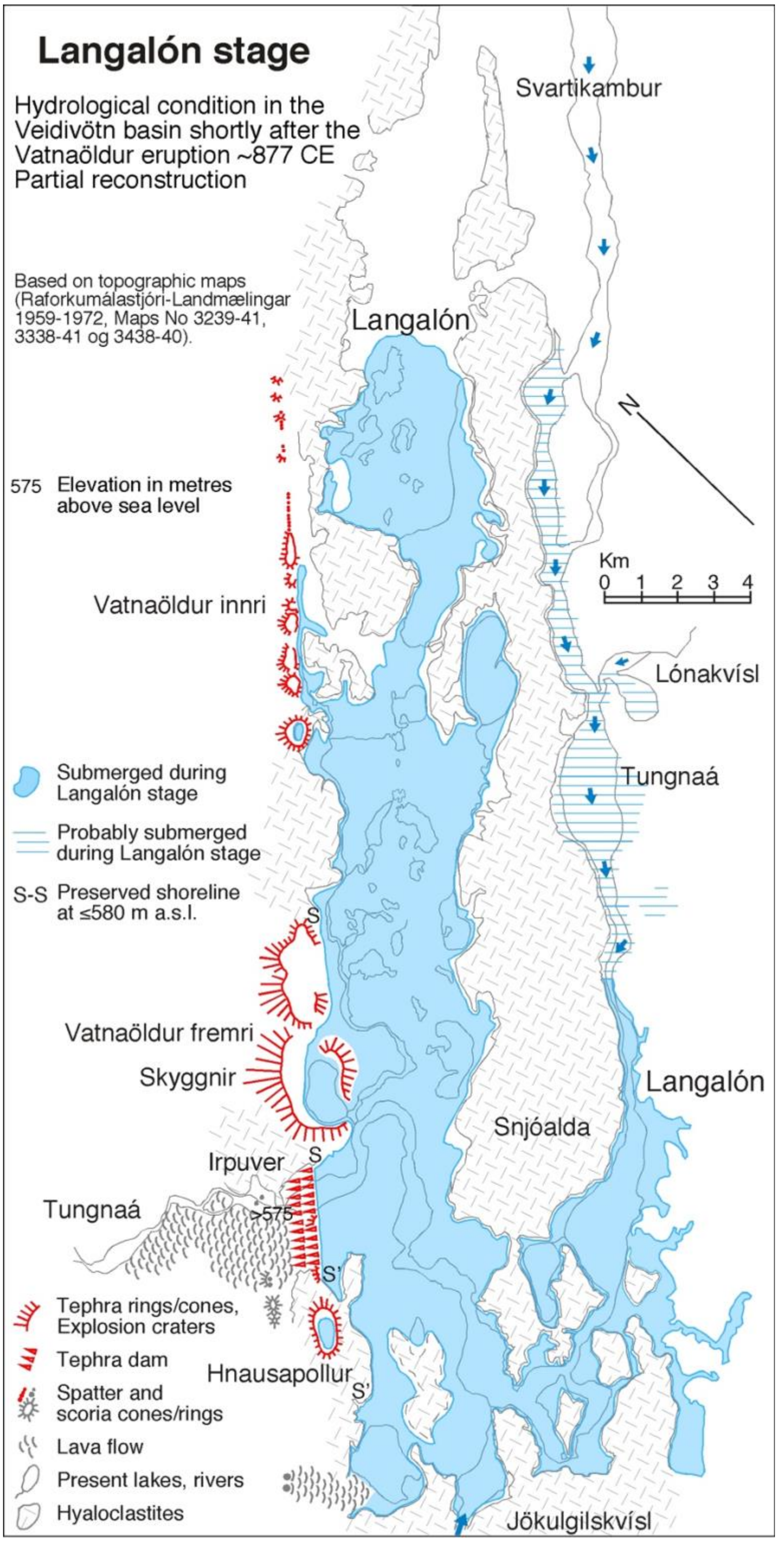

Figure 6: Past hydrological conditions in the Veidivötn basin. Area likely to have been under water during the Langalón stage, following the Vatnaöldur eruption 877 CE. Drainage control by the Langalón tephra dam near Irpuver, minimum elevation ≥575 m a.s.l. Lake level is shown at 580 masl. Red hatched: Vatnaöldur tephra rings. Red triangles: Langalón tephra dam (triangles where it eroded away, note the small crater remnants – hatched – of the dam). Blue: Langalón temporary lake. Light blue/sparsely ruled: Stórisjór, a potential lake in part of the Tungnaá river bed when 5 m of tephra have been removed. See also Appendix, Fig. 1-2.

Shorelines of a lake have been found in the Vatnaöldur tephra in several places (S-S' on Fig. 6, Fig. 7a). Comparison to maps with 5 m contours indicates elevations close to 580 m a.s.l. for shorelines in areas that were not submerged by younger temporary lakes of the Kýlingalón stage (section 5.7), best developed on the SE slope of Tjörvafell hill and on both sides of the isthmus between the hills (Fig. 7b). In the SW end of the basin and in the river basin of Tungnaá the highest shoreline lies at roughly 580 m a.s.l. (582.5 m a.s.l. by reference to Sudurlína pylon), but interference with younger Kýlingalón shorelines makes this maximum uncertain.

Disregarding tilting or subsidence during the next eruption, it can be assumed that the maximum lake level during the Langalón stage was between 575 and 580 m a.s.l. Lake level at 580 m a.s.l. (Fig. 6) is shown here as a worst-case scenario.

The areal of Langalón as shown on Fig. 6 is ca 140 km^2. The total volume of water cannot be calculated because the bathymetry of basin is not known in detail. However, every 1 m rise in lake level above 570 m a.s.l. added at least 0.1 km^3 to its volume. Maximum dischargeable volume, if lake level fell from 580 to 565 m a.s.l. in a single flood, was of the order 1.5 km^3 (1500 GL). If lake level fell to 560 m a.s.l. in a single flood, this volume would increase to ca 1.9 km^3. Comparable volumes, if lake level fell from 575 to 565 or 560 m a.s.l. in a single flood, are ca 0.8 and ca 1.1 km^3, respectively.

The riverbed of Tungnaá upstream from the basin, at the confluence with the Lónakvísl river, was up to 9 m lower before the Veidivötn eruption ca 1477 CE than at present (based on re-evaluation of data in Tómasson and Vilmundardóttir 1967), or close to 575 m a.s.l. Tómasson and Vilmundardóttir demonstrated that a lake, which they named Stórisjór, could have existed in this area. Depending on the actual lake level of Langalón, a temporary lake may therefore have extended along the (then lower) bed of Tungnaá farther upstream than shown by the blue area on Fig. 6. Its potential extension at 580 m a.s.l. is shown by sparse ruling.

The discharge into Langalón by surface and ground water may have been lower than today, in particular if Tungnaá had no glacial component at that time as indicated by diatome populations in the pre-1477 sediments (Tómasson and Vilmundardóttir 1967). About 140 days are needed to increase the lake volume by 1 km^3 using the average discharge of Tungnaá through the Irpuver pass, ~80 m^3/s or ~7 million m^3/day (Jónsdóttir and Einarsson 2003), about 200 days using the spring-fed discharge of 52 m^3/s or 4,5 million m^3/day (Pálmarsson 2009) and about 1 year using minimum discharge of 32 m^3/s or 2.8 million m^3/day (Egilson 2016). Recovery time for Tungnaá and Jökulgilskvísl, due to tephra deposition within the Tungnaá basin, has not been estimated and is not included. At least 1 m thick alluvial material from Jökulgilskvísl was deposited on top of the Vatnaöldur tephra in the SW part of the basin (Fig. 5) during the Langalón stage. This deposit could, however, have formed in a relatively short time as a result of increased flow rate during the emtying of the lake.

The emtying of Langalón may have taken place as a single event. The tephra in the crater remnants (hatched lines between the triangles) and flank deposits of the former dam, is compacted but not consolidated and the dam may have eroded easily - and fast - once overtopping began. Undercutting may also have initiated the dam failure. The resulting flood transported tephra and rock debris onto the lava fields to the west and down the riverbed of Tungnaá. Bars and channels mark its course on the Tjörvahraun lava W of Vesturbjallar where waterlaid debris can be traced for >10 km. The former lake Krókslón, about 10 km downstream from the dam, was flooded and emtied as a result of the Vatnaöldur eruption (Larsen 2019).

Assuming that the tephra dam was lowered from 580 to 565 m a.s.l. in five hours the maximum peak flow was 5000-10000 m^3/s (Walder and O'Connor 1997; Gudmundsson, pers. comm.).

Figure 7a. The shoreline of the Langalón lake at appoximately 580 m a.s.l. on the lower southeast slope of Tjörvafell hill. The big rock on the hillside is at 670 m a.s.l. Here only one shoreline is discernible as a break in slope and changed or no vegetation. In some places "washed" (fines depleted), uncompacted Vatnaöldur tephra is found below/at the break. See also Appendix, Fig. 3-1.

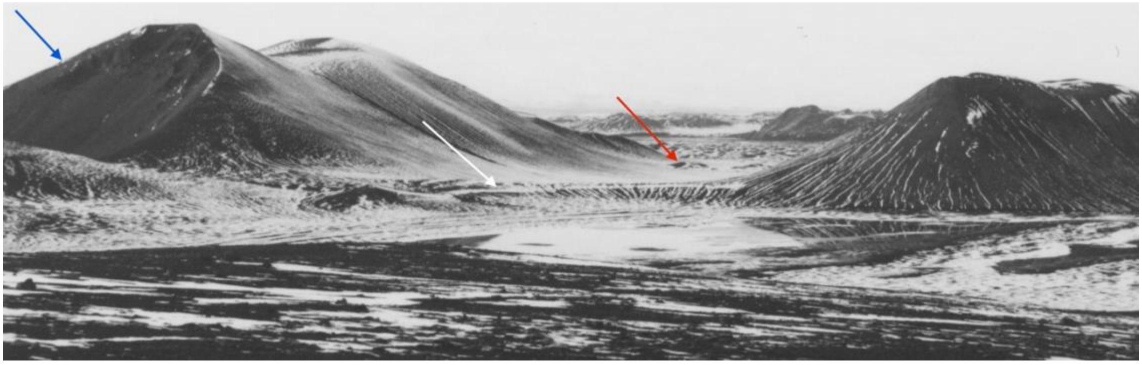

Figure 7b. Close-up of the low istmus (white arrow) between Hnausapollur explosion crater (blue arrow) and an unnamed hyaloclastite hill to the right. A distinct white shoreline (with snow-cover) on the istmus lies at about 580 m a.s.l. It can be followed onto the slopes of Tjörvafell to the left but is almost impossible to follow in the loose scree on the hill to the right. The shoreline is also evident on the other side of the ísmus. Behind the istmus are remnants of four small tephra cones of the Vatnaöldur eruption (red arrow) see also Appendix, Fig. 3-2. They were part of the tephra dam holding up the Langalón lake.

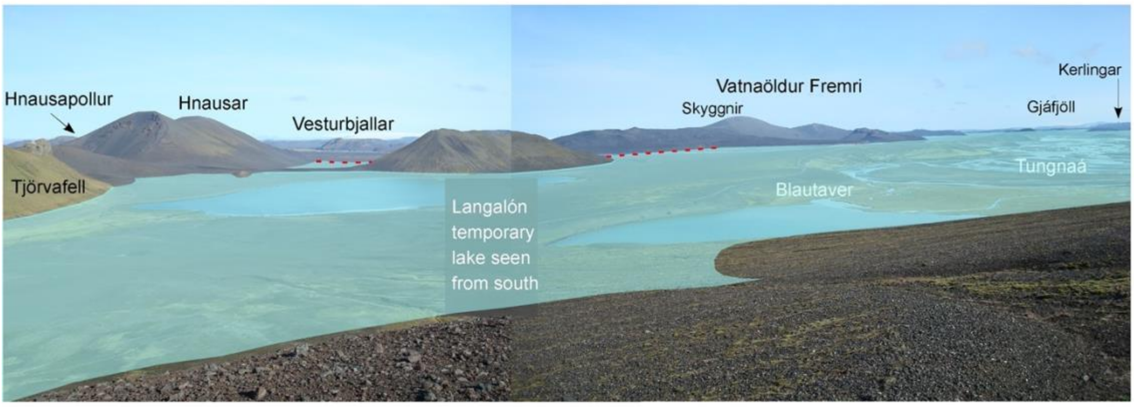

Figure 7c. Composite photograph with blue overlay at water level 580 m a.s.l. View to the north from a hyaloclastite hill at Ljótipollur. Note the istmus and the water beyond. Red dotted line indicates the tephra dam. Based on shorelines at Tjörvafell, water marks at the Vatnaöldur Fremri tephra rings and shorelines along Tungnaá (see also Appendix, Figs. 2-1 to 2-6, 3-3, 5-1, 5-2).

However, if the dam was lowered from 580 to 560 m a.s.l. in five hours the maximum peak flow was 10000-20000 m^3/s. Peak discharge of the Thjórsá river at Búrfell, about 50 km downstream from the dam, never exceeded 10000 m^3/s. Airborne tephra from the Vatnaöldur eruption is preserved on riverbanks that would have been flooded in such a case.

The failure and erosion of the nearly 3 km long Langalón tephra dam, potential scenarios, flood routes and peak flows will be treated elsewhere (Gudmundsson and Larsen in prep). The bed of the Tungnaá river down-stream from Irpuver through the Sigalda canyon most likely acquired its present form in this large flood.

5.5 The Fiskivötn stage

The name "Fiskivötn" (Fishing lakes) appears in the old Icelandic literature and refers to a group of inland lakes in South-central Iceland, but of otherwisely unknown location. A 16th century map (Sigurðsson, 1971) based on conventional knowledge rather than contemporary inspection, shows four interconnected lakes with this name. Tradition has placed Fiskivötn in the Veidivötn basin and here we adopt the name for the stable stage that followed the emptying of Langalón and lasted until the 1477 CE Veidivötn eruption (section 5.6).

After the emptying of Langalón, the surface drainage from the basin was controlled by the lava flows THi and THj near Irpuver. The flood almost certainly eroded the surface of the lavas and the river bed of Tungnaá, possibly down to 560 m a.s.l. The following ca. 600 year period was stable in the sense that no volcanic events took place in the Veidivötn basin. Gradual changes probably continued throughout the Fiskivötn stage.

In the NE and central part of the basin (now occupied by the Veidivötn lakes) filling in by the Vatnaöldur tephra was substantial. Red dots on Fig. 8 indicate reworked tephra above 560 m a.s.l. It is therefore likely that the Fiskivötn “bottom” of the basin was lowest along the SE margin and rose gradually towards the NW margin and the Vatnaöldur crater row. Some estimates of water depth can be made at the margins of the basin where only airfall tephra was deposited during the Veidivötn eruption 1477 CE: About 5 m of Veidivötn tephra were deposited along the NW margin (Fig. 3 lower panel). Up to 10 m were deposited along the SE margin where the four older generation lakes now lie (for bathymetry see Rist 1975). Disregarding subsidence of the basin, as well as post-eruption deposition in the lake bowls, the Fiskivötn "bathymetry" included spots of <560 m a.s.l. near the NW margin and depressions at about 535, 540, 555 and 560 m a.s.l. at the SE margin when the tephra had been removed. Areas that were submerged at lake level ≥560 m a.s.l. are dark blue on Fig. 8. Areas that were probably submerged are medium blue and those where flats of wet sediment/shallow water are likely to have dominated are pale blue.

In the SW end of the basin, the rivers Tungnaá and Jökulgilskvísl eroded a channel (Fig. 8, small blue dots) into the alluvial sediments that had accumulated to ~572 m a.s.l. during the Hnausalón and Langalón stages (bold blue dots on Figs. 4 & 8, see also Fig. 5). It is not possible to see how deep this channel had become when filled up by tephra during the Veidivötn eruption (section 5.6). The course of the rivers downstream from the "channel" is inferred by waterworn rhyolite pebbles in the ejecta from two craters of the Veidivötn eruption that opened up through alluvial deposits. No deposits from this stage are exposed above their crater floors at ~565 m a.s.l. (black triangles <565 on Fig. 8). A partly submerged delta and a shallow lake are therefore considered the most likely environment in the SW part of the basin during the Fiskivötn stage.

The geometry of the lake system in the basin can thus be crudely reconstructed. Depending on the surface elevation of the lava flow at Irpuver and the gradient in the basin, lakes could have

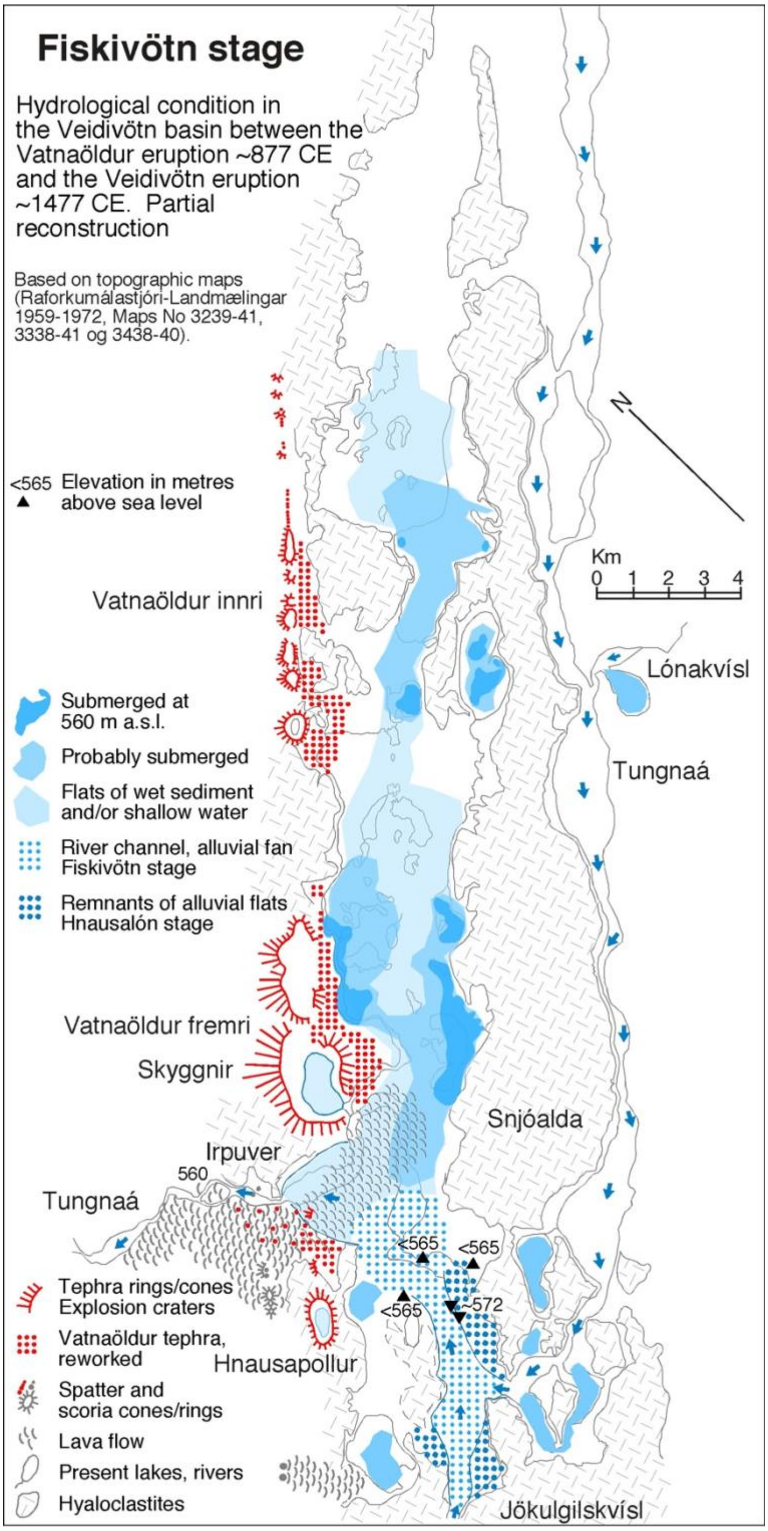

Figure 8. Past hydrological conditions in the Veidivötn basin. Areas likely to have been under water during the Fiskivötn stable stage, late 9th century to 1477 CE. Drainage control at Irpuver at ~560 m a.s.l. Submerged areas at water level of ≥560 m a.s.l. Red: Vatnaöldur tephra rings (hatched lines) and reworked tephra (dots). Dark blue: areas below 560 m a.s.l. after removing 5 and 10 m of tephra from the SE and NW margins of the basin, respectively. Medium and pale blue: other areas likely to have been below 560 m a.s.l., including those currently below tephra rings of the Veidivötn eruption. Large blue dots: remnants of alluvium from the Hnausalón and Langalón stages. Small blue dots: the river channel cut by the Tungnaá and Jökulgilskvísl rivers and their delta during the Fiskivötn stage (see Appendix, compare Figs. 1-1 and 1-3). Black triangles with numbers indicate elevations, see main text.

existed in four to six areas but the degree of interconnection is not known, nor the number of the one-time "Fiskivötn" lakes.

5.6 The Veidivötn eruption 1477 CE

About 40 km of the 65 km long Veidivötn volcanic fissure opened along the middle of the basin (Larsen 1984, Larsen et al. 2013, Vilmundardóttir et al. 1988). The 1477 CE eruption was a predominantly explosive hydromagmatic eruption that primarily produced basaltic lapilli and ash sized tephra, often with abundant lithic material. The volume of basaltic tephra is of the order 10 km^3 as freshly fallen. The craters (shown in red on Fig. 1 and 9) are of three types. Tephra rings and cones, often as interlocking crater rows several km long, resulted from explosive activity where the volcanic fissure opened up through wet areas such as a river delta and lacustrine sediments, and are shown by red hatched lines. During the later stages the eruption on some fissure segments became effusive, forming spatter cones/rings nested within the tephra craters, shown by red dots (Fig. 9) and small lava flows (not indicated). The secondary craters, irregular formations of scoria and spatter resulting from the lava flowing into wet areas and interacting with water or water-logged sediments, are shown by thin red lines.

Large-scale topographic changes took place in the Veidivötn basin during the Veidivötn eruption, caused by accumulation of volcanic material and coring out of underlying strata. Accumulation was greatest along the middle of the basin, where 20-100 m high crater rims (above the 560 m a.s.l. reference level) formed on each side of the volcanic fissure. Coring dominated above the conduits (Giniaux 2013). Along the edges of the basin accumulation was much less, in places only 5-10 m, which then became the lowest areas. Lava from the later effusive activity either ponded within the tephra rings or flowed towards the lowest lying areas where it interacted with water and sediment forming secondary craters (Fig. 9).

The effects of the Veidivötn eruption on the lake system in the Veidivötn basin and the rivers that drain the adjoining areas were both temporary and permanent. The immediate effects on the hydrology of the Veidivötn basin were to: 1) destroy the pre-eruption lake system, the old Fiskivötn lakes; 2) close the old course of Tungnaá river through the basin; 3) change the capacity of the groundwater reservoir in the basin. Substantial volume of water was used to convert magma into tephra during the eruption (see Discussion). Short term effects included perturbations of surface drainage and formation of unstable lakes, the Kýlingalón stage. Long term effects included permanent raise of groundwater level and developement of new lake- and drainage system, the Veidivötn stage.

5.7 The Kýlingalón stage

Three temporary dams or barriers formed in the old bed of the Tungnaá river as a consequence of the Veidivötn eruption. Two small temporary barriers affected the drainage of the middle part of the Veidivötn basin. The barries were crater rims and in one instance a failed crater flank.

At least four unstable lakes were held up behind the temporary dams (Fig. 9). They have been named Kýlingalón, Skálavatnslón, Nýjavatnslón and Snjóöldulón after the largest lakes now remaining in their basins (for local names see Fig. 2). The first two lakes left clear shorelines as an evidence of their existence, the remaining two left occasional lines or benches but otherwise their existence is inferred by the topography. See also Appendix 5 & 6.

The damming of river Tungnaá and the Kýlingalón temporary lake

Two dams contributed to the formation of the Kýlingalón lake in the Tungnaá river bed. The uppermost dam formed in the channel that Tungnaá and Jökulgilskvísl had eroded into the

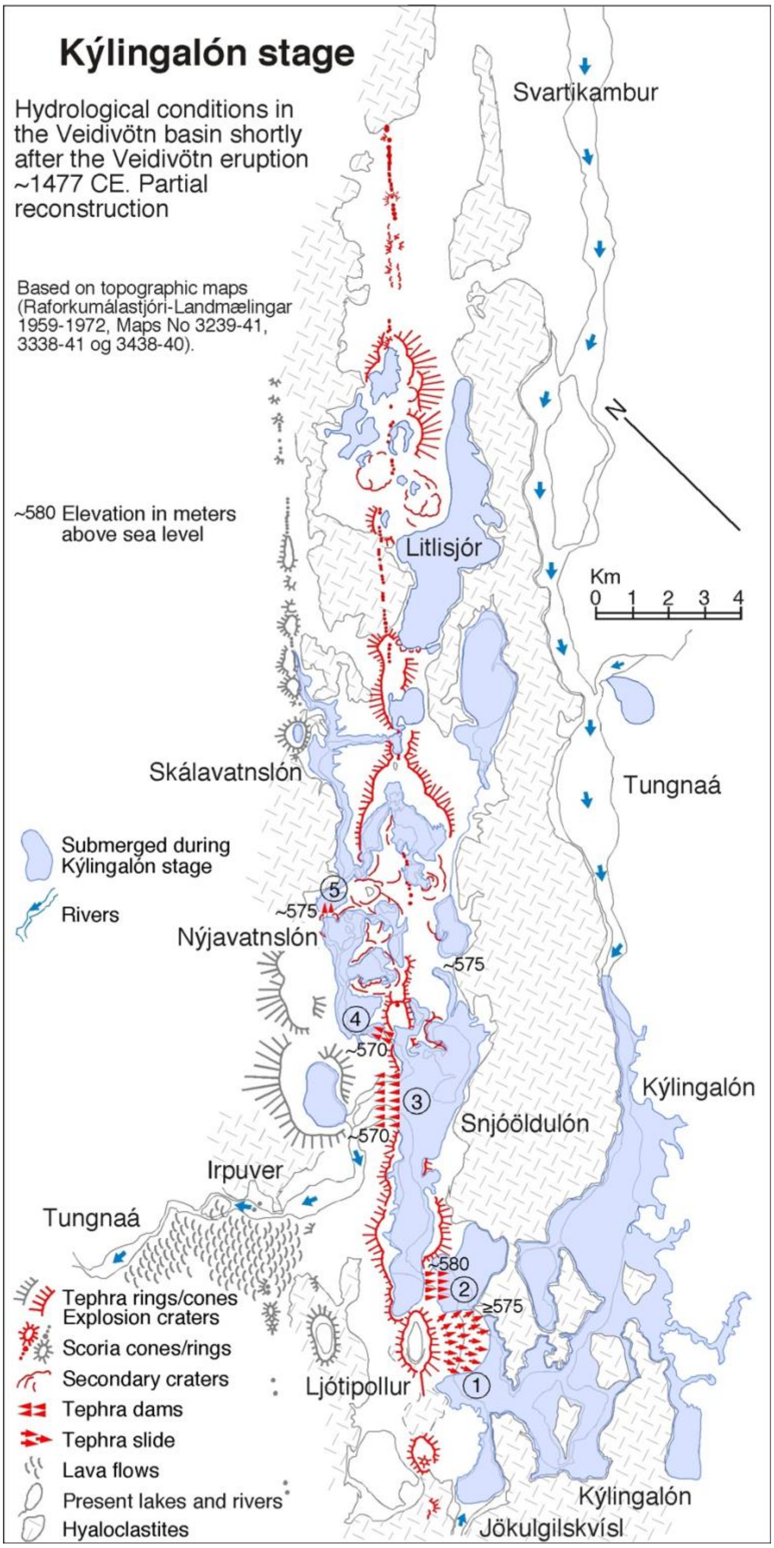

Figure 9. Past hydrological conditions in the Veidivötn basin. Area likely to have been under water during the Kýlingalón stage, in the years/decades following the 1477 CE Veidivötn eruption. Blue: the lake system at maximum extension. Red: Veidivötn craters (hatched lines), triangles indicate the eroded tephra dams, arrows indicate tephra slide. Drainage control: Five tephra dams (1-5) with crests between 570 and 580 masl. 1: Ljótipollur tephra slide. 2: crater rim of the main dam, controlling the lake level of Kýlingalón. 3: Svartikrókur crater rims damming the Snjóöldulón lake. 4 and 5: crater rims damming Nýjavatnslón and Skálavatnslón. See also Appendix, Figs. 4-1 to 4-6.

older alluvial deposits during the Fiskivötn stage (cf. Fig. 8). The SE flank of a 1477 CE explosion crater, Ljótipollur, failed and slid into the ca 0.7 km wide channel and plugged a 1.5 km long stretch of it (1 on Fig. 9, red arrows). The slide was partly halted by the ca 5 m gravel bank on the far side of the channel (Fig. 5 and 10 a), but some material continued onto the alluvial terrace beyond the channel. The slide material was spatter, at various stages of fusion or consolidation (Appendix 4), and compacted ash and scoria. The uneven surface of the slide in the old channel is at ~595 m a.s.l. where highest. The lowest part of this dam was the alluvial terrace of ~572 m a.s.l. (Fig. 5), capped by some meters of slide material that thinned away from the channel. The minimum elevation is therefore not known but is set at ≥575 m a.s.l. for reference when the emptying of Kýlingalón is discussed.

The other and higher dam (hereafter the main dam) across the old bed of Tungnaá was formed by the rims of interlocking tephra rings about 1 km farther downstream (2 on Fig. 9, red triangles pointing right). Here the volcanic fissure had opened up through the delta of the Tungnaá/Jökulgilskvísl rivers (compare Figs. 8 and 9, Appendix Figs. 4-1 and 4-2). The material in the crater rims is bedded lapilli and ash mixed with abundant alluvial material ranging from cobbles down to silt. This tephra is very compact, the grain size distribution allows dense packing and the sediment probably acted as a grout to make it nearly impervious. Shorelines at roughly 580 m a.s.l. are discernible on the crater flanks on each side of the 0.6 km breach that formed when the dam failed (Fig. 10 b). The lowest part of the rims forming the dam can therefore be set at ca 580 m a.s.l. Height above the pre-eruption alluvium was >15 m.

Shorelines of a large lake can be seen on either side of the Tungnaá river, upstream from the dams. Distinct shorelines are found on the slopes of the hyaloclastite hills within and around the lake (Fig. 10 c-f). In some localities 2-4 successive shorelines are discernible, depending on the material on the slopes (Fig. 10 d), elsewhere only a single line is preserved (Fig. 10 f). The highest and most distinct of the shorelines lies at about 582 m a.s.l. at Austurbjallar, determined by reference to the base code of a pylon in the Sudurlína transmission line (white arrow on Fig. 10 e). Each of the lower shorelines drops a few meters and is usually less distinct than the higher ones. At Austurbjallar the highest shoreline is best developed with up to 2 m wide bench where it is eroded into thick deposits of the tephra from the Vatnaöldur eruption 877 CE. Where shorelines are eroded into the Vatnaöldur tephra, one or more line may be a relic from the Langalón stage or a line rejuvenated during the Kýlingalón stage. The bench of the highest shoreline at Austurbjallar has a ≥0.5 m thick cover of "water-worn" (rounded-subrounded grains), water-deposited Veidivötn tephra, indicating that the shoreline was either formed or rejuvenated by the Kýlingalón lake. Where multiple shorelines are eroded into material deposited by the Veidivötn eruption, e.g. flank deposits just upstream from the Ljótipollur tephra slide (Appendix 5) all must belong to the Kýlingalón lake. At least three shorelines, including the highest line, are thus known to record changes of the lake level of Kýlingalón.

The areal of Kýlingalón as shown on Fig. 9 was about 35 km^2. Dischargeable volume was calculated from maps with 5 m contours and was close to 0.3 km^3 or 300 GL at lake level of 580 m a.s.l. (Table 1 and Fig. 11). Maximum areal may, however, have exceeded 37 km^2. Filling time to 580 m a.s.l., under present-day conditions, can be calculated from the discharge of Tungnaá and Jökulgilskvísl. Using the average discharge of 60 m^3/s (less the 19.5 m^3/s of Vatnakvísl, (Jónsdóttir and Einarsson 2003; Pálmarsson 2009), filling time is about 60 days. Recovery time for Tungnaá and Jökulgilskvísl, as a consequence of tephra deposition within the Tungnaá basin, has not been estimated and is not included. If Tungnaá had no glacial component at that time (Tómasson and Vilmundardóttir 1967), its discharge would have been

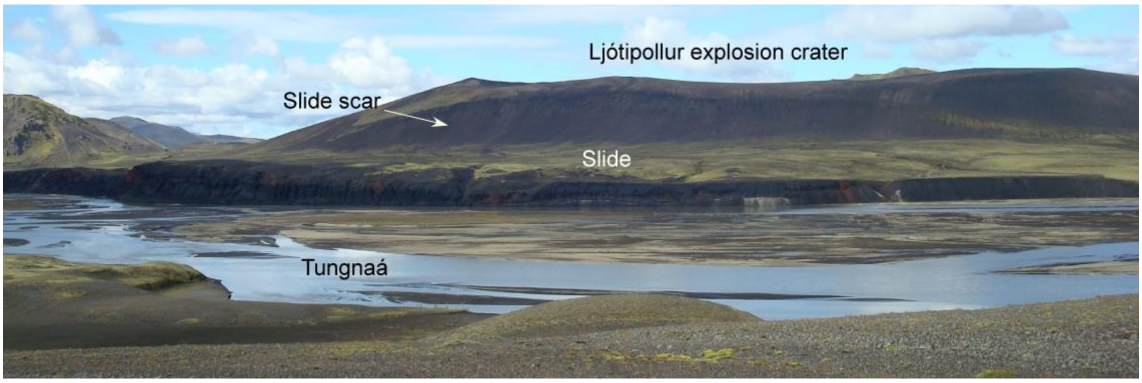

Figure 10 a. Tephra slide from Ljótipollur flank failure formed the upper Kýlingalón dam, here seen from SE. The slide scar is darker than the flat vegetated slide surface. Light coloured rhyolite gravel of buried alluvial terrace is seen below the slide material, see also Appendix 4. The slide filled the pre-eruption bed of the Tungnaá river (on the other side of the terrace remnant). The river eroded a new channel along the slide. For location of the photos in Fig. 10 see Fig. 5-5 in Appendix 5.

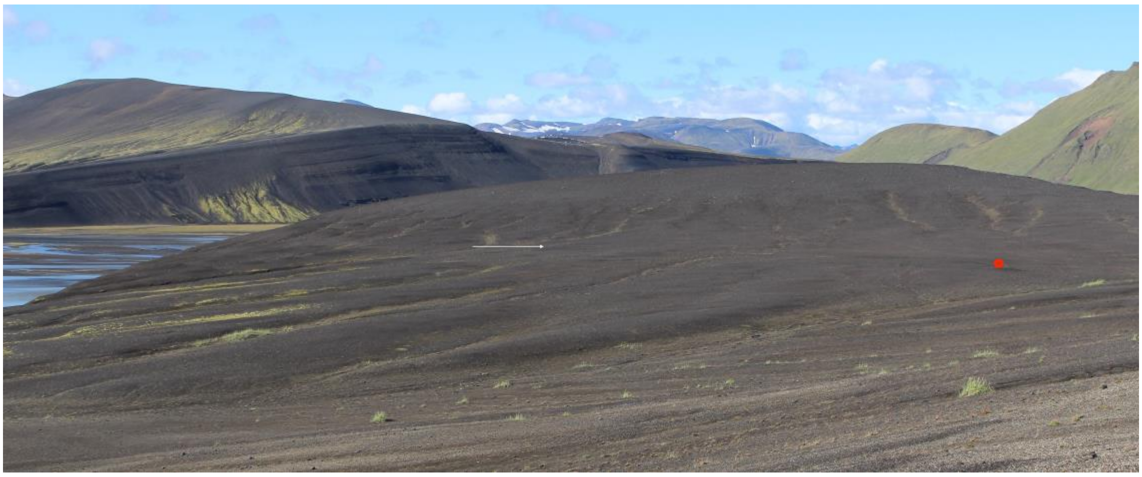

Figure 10 b. The breached tephra dam (main dam) between the rims of Ljótipollur crater (top, left) and adjacent Svartikrókur crater (closer), Tungnaá flows to the right through the breach. Highest water level of the Kýlingalón lake on the crater flank is indicated by white line. Red dot is 1.7 m across. Note the change in slope and appearence from gentle sloping smooth surface at the top of the crater rim to water carved/washed surface below the level of the lake. View towards SW. Photo Adalsteinn Eiríksson.

Figure 10 c. Two distinct shorelines and a third indistinct line (lowest) in the east slope of Aldan hill, Kýlingar area, resulting from damming of the Tungnaá river. They indicate lake levels of Kýlingalón temporary lake that formed after the 1477 CE Veidivötn eruption, the upper line may be rejuvenated Langalón shoreline. View toward NW, Kýlingavötn lake in foreground.

Figure 10 d. Three (to four) shorelines near Austurkrókur, note the 1 m long spade (in white circle, uppermost line). Here the middle line is most prominent. View towards S across the Tungnaá river to Barmur, Torfajökull area. For location of the photos in Fig. 10 see Fig. 5-5 in Appendix 5.

Figure 10 e. Shorelines of Kýlingalón - and Langalón - at Austurbjallar between the lakes Austurbjallavatn and Litla Austurbjallavatn (to the left beyond the dry flats). The uppermost shoreline is cut into tephra from the 877 CE Vatnaöldur eruption and is overlain by "water-transported" tephra from the 1477 CE Veidivötn eruption. Arrow shows where elevation (582.5 m a.s.l.) was determined by reference to the base code of Sudurlína pylon and the section measured (see main text). Red circle is 1.8 m in diameter. View towards N.

Figure 10 f. Shoreline, defined by yellow-green vegetation, along the Tungnaá river (north bank) at Hnaus mountain, 5 km upstream from Ljótipollur crater. Pylon for scale. View towards NW across the Tungnaá river from Stóri Kýlingur hill.

much less. The spring-fed component of Tungnaá/Jökulgilskvísl rivers is now about 32 m^3/s (Pálmarsson 2009) and could fill Kýlingalón in about 100 days.

Failure of the main dam, a crater wall of unwelded but densely packed, sediment mixed tephra, was most likely brought about by overtopping. Erosion of the unwelded tephra, however compact, is likely to have been rapid once it started. A spring flood rafting of ice and tephra is one possibility to initiate the dam failure. However, the emptying of Kýlingalón was complicated by the presence of the second but lower dam (Ljótipollur tephra slide) upstream from the main dam (and a lower dam downstream, see Snjóöldulón). The lake level may have lowered down to that of the tephra slide (≥575 m a.s.l.) during the first stage of the emptying, in which case ca 0.15 km^3 or 150 GL drained from the lake. The fused/consolidated scoria and spatter in the slide was more resistant to erosion by water than the tephra in the main dam. Finally, a new channel was eroded along the tephra plug through the tephra-capped alluvial sediments, most likely by undercutting the unconsolidated sediments, followed by collapse of the more resistant tephra cap. Spring floods may have been crucial in eroding the second dam.

The peak flow in the dam failures of Kýlingalón was, apparently, not as high as those postulated for Langalón dam failure. When the main dam failed the water was deflected by 90° as it entered the adjacent Svartikrókur crater row (see Snjóöldulón), following it for 5 km until the flood cut through its crater walls in a “hair-pin bend” onto the lava fields (Fig. 9). This gate is now 0.5 - 1 km wide but the flow velocity in this roundabout channel is unlikely to have been very high. Maximum discharge was possibly a few thousand m^3/s. Details will be treated elsewhere (Gudmundsson and Larsen in prep).

The lifetime of the lake is not known. The highest shoreline is well enough developed (Fig. 10 c-f) to indicate a constant water level for some time. However, floating ice or tephra rafts may have enhanced it, e.g. during spring flood, and it may also be a rejuvenated Langalón shoreline. Lifetime at the highest water level is therefore thought to be of the order of months rather than years. The more resistant dam formed by the tephra slide may have controlled the water level for months or years after the failure of the main dam. If the shorelines record lowering of the dams during successive springfloods, total lifetime, until Kýlingalón had completely emptied, may have been 3-5 years.

The Snjóöldulón temporary lake

A long and low dam was formed by the interconnected NW rims of the Svartikrókur tephra rings downstream of the main dam. The rim opposite the breached main dam was severely eroded but was apparently not overtopped at ≤575 m a.s.l. The part that failed (3 on Fig. 9, red triangles pointing left) must have been lower still. The breach through which the Snjóöldulón temporary lake (and all the other unstable lakes) emptied is 1.2 km wide at present. A remnant of an apparent "spillover" at the SW end of the breach lies at ~570 m a.s.l. and the elevation of this dam was consequently set at ≥570 m a.s.l.

A lake occupying the bowls of the Svartikrókur tephra rings and extending somewhat farther east than the present Snjóölduvatn lake (faint outline in grey on Fig. 9), is inferred from the topographic conditions rather than direct evidence in the form of shorelines. No distinct shorelines have been found in the area that must have been inundated at a lake level of 570 m a.s.l. or thereabouts. Evidence of higher lake level than at present can be seen in some localities around the Snjóölduvatn lake and a bench at its original outlet* may have formed during the emptying of the temporary lake (Appendix 6). *A new outlet of Snjóölduvatn was excavated in the 1980ies.

The areal of the lake at 570 m a.s.l. as shown on Fig. 9 was 11.5 km^2 and dischargeable volume above 562 m a.s.l. was 0.067 km^3 or 67 GL (Table 1 and Fig. 11). The source of the water in Snjóöldulón could have been the springs feeding the present day Snjóölduvatn (2.5 m^3/sec, Pálmarsson 2009), filling such lake in ~10 months, and seepage from Kýlingalón. The absense of distinct shorelines indicates that the water level never became stable during its lifetime and it may not have reached 570 m a.s.l. until flooded from Kýlingalón.

The emptying of Snjóöldulón is likely to have been triggered by the failure of the main dam of Kýlingalón. If Snjóöldulón was at lake level 570 m a.s.l. when the main dam failed and Kýlingalón was lowered down to 575 m a.s.l., about 0.22 km^3 or 220 GL could have drained from the lake basins in a single event.

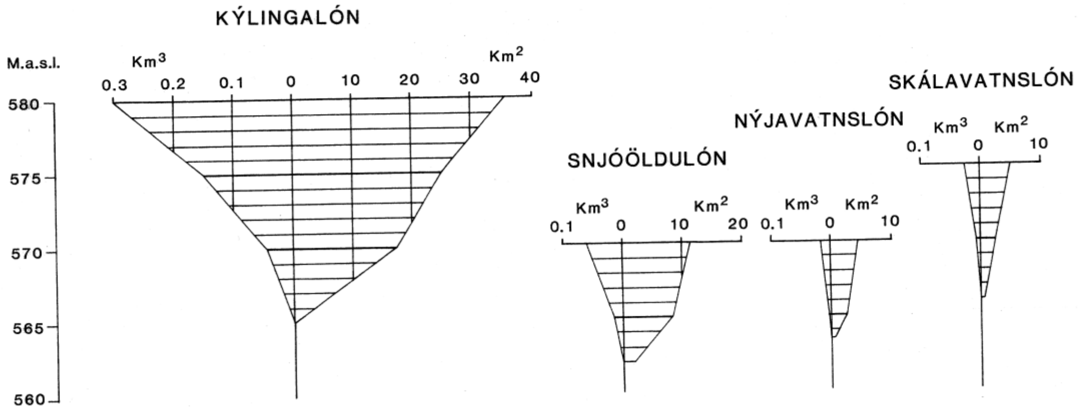

Figure 11. Maximum area and dischargeable volume of the four temporary lakes of the Kýlingalón stage.

Skálavatnslón and Nýjavatnslón temporary lakes

Barriers formed by crater rims (4 and 5 on Fig. 9) retained water from the middle part of the basin. The material in the rims is bedded loose ash and lapilli, with intercalated layers of welded spatter and occasionally a lining by lava.

The presence of a temporary lake, Skálavatnslón, either held up by crater rims at ~575 m a.s.l. or a crater flank about 1 km farther upstream, and extending into several of the present Veidivötn lakes (Fig. 9), is borne out by shorelines ranging from well-developed benches to faint "bath-tub marks" (see Appendix 6). Shorelines lying between 570 and 575 m a.s.l. can be seen on the inner slopes of the large tephra ring around lakes Skálavatn and Langavatn (for local names see Fig. 2). Up to three successive shorelines are present in some of the localities, e.g. at the SW end of Langavatn lake. Less distinct watermarks or "bath-tub marks" lie close to the present 575 m a.s.l. contour line along the Vatnakvísl river (see Appendix 6). Maximum lake level of Skálavatnslón cannot be determined from the available data. The extension at lake level 575 m a.s.l. is shown on Fig. 9.

The areal of Skálavatnslón at lake level 575 m a.s.l. was 5 km^2 and dischargeable volume was about 0.025 km^3 or 25 GL. Filling time cannot be estimated but Skálavatnslón cannot have formed until the groundwater reservoir in the Veidivötn basin had recharged. The emptying of the lake was probably stepwise because of the many barriers. It discharged into the adjacent Nýjavatnslón.

The temporary Nýjavatnslón was held up by a barrier at the intersection of crater rims that are now cut by a ca 100 m wide channel with deposits at ≥575 m a.s.l. on both sides (Fig. 9). The most likely elevation of the barrier was 570-575 m a.s.l. The lake held up behind this dam is inferred from occasional shorelines, washed surfaces and topographic conditions.(Appendix 6).

The areal of Nýjavatnslón as drawn at lake level 570 m a.s.l. was 4.6 km^2 and dischargeable volume was about 0.016 km^3 or 16 GL. Filling time and lifetime are not known. As in the case of Skálavatnslón, Nýjavatnslón cannot have formed until the groundwater reservoir had recharged. If both lakes emptied at the same time about 41 GL could have drained from these lake basins in a single event.

Lake	Water level m a.s.l.	Areal km^2	Dischargeable volume, km^3	Bottom depth m a.s.l
Kýlingalón	580	35.5	0.302	
--	575	25.0	0.150	
--	570	17.5	0.045	
--	565	0	0	565
Snjóöldulón	570	11.5	0.067	
--	565	8.8	0.016	
--	562	1.6	0	
--				540 (pit)
Nýjavatnslón	570	4.6	0.016	
	565	2.5	0.003	
	563.5	0.9	0	
				533 (pit)
Skálavatnslón	575	5.0	0.025	
--	570	2.5	0.006	
--	566	0.5	0	
				533 (pit)
All lakes			0.410	

Table 1. Area and volume of unstable lakes following the 1477 CE Veidivötn eruption. Bathymetry from Rist (1975).

In summary, the probable order of dam failures and emptying of the four lakes was as follows: Failure of the main dam of Kýlingalón lake and lowering the lake level down to the Ljótipollur tephra slide, with consequent failure of the dam at Svartikrókur and empying of Snjóöldulón. Gradual erosion of the Ljótipollur tephra slide followed. Skálavatnslón probably emptied stepwise into the Nýjavatnlón with consequent overtopping until both lakes had emptied.

The duration of the Kýlingalón stage, until all unstable lakes had emptied, was years to decades, depending on how fast the groundwater reservoir in the Veidivötn basin recharged (see Discussion).

5.8 The Veidivötn stage

The present stable stage, the Veidivötn stage, is characterized by numerous small lakes that lie within the crater formations of the 1477 CE eruption in the Veidivötn basin and several larger lakes that lie between the 1477 CE volcanic products and the hyaloclastite formations at the edges of the basin (Fig. 12). The latter are remnants of the previous generation of lakes in the basin, the Fiskivötn lakes. They are collectively referred to as "older generation" lakes. The lava flows THj and THi still control the outflow from the basin at ~560 m a.s.l.

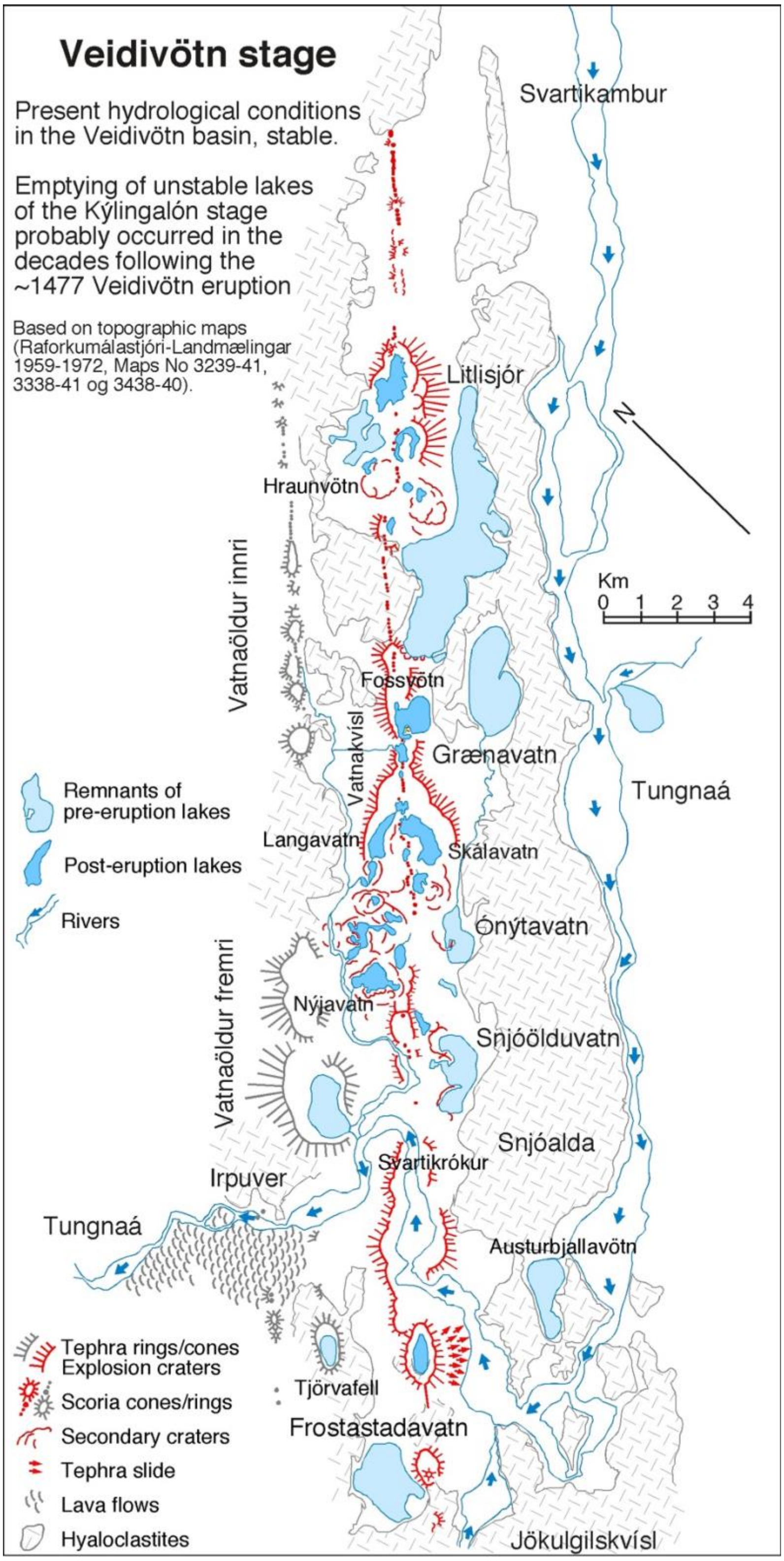

Figure 12. Present hydrological conditions in the Veidivötn basin. All lakes are shown in blue, darker colour post-eruption/younger generation lakes. Drainage from SW and middle part of the basin is controlled by the lava flows at Irpuver at about 560 m a.s.l. Tungnaá river now flows past the partly eroded tephra slide (red arrows) and through the row of tephra rings at Svartikrókur until taking U-turn towards Irpuver pass. Vatnakvísl river drains the middle part of the basin. The NE part has, however, no surface drainage.

The older generation of lakes are Litlisjór (587.4 m a.s.l.), Grænavatn (579.1 m a.s.l.), Ónýtavatn (573.4 m a.s.l.) and Snjóölduvatn (562.3 m a.s.l., Pálmarsson 2009) , which all lie along the SE edge of the basin, and the northernmost of the Hraunvötn lakes, which lies at its NW edge (Fig. 12). Frostastadavatn, also at the NW edge of the basin but at the other end, lies in a depression sealed off by volcanic products of the 1477 CE Veidivötn eruption. These six lakes are the largest lakes in the basin, 1-9.2 km^2, with volumes ranging between 5.7 and 66.7 GL (Rist 1975). Lake level ranges from 562 m a.s.l. at Snjóölduvatn to 590 m a.s.l. at Hraunvötn, rising generally towards NE, and maximum depth ranges from 14 to 23 m. The older generation lakes have smooth outlines and gently sloping floors except where bordered by the 1477 CE volcanic products, in which case rugged shores and pitted floors are common.

A younger generation of lakes occupies depressions within the 1477 CE volcanic products, such as the bowls of primary and secondary craters, former lava lakes, explosion pits, etc. All told they exceed 40, but the number varies with changes in the local ground water table. The size of the lakes varies from some tens of m^2 to 0.78 km^2. The largest 12 lakes have volumes ranging from 0.1 GL to 4.4 GL (Rist 1975). Lake level ranges from 564.3 m a.s.l. at Nýjavatn to 590.2 m a.s.l. at Hraunvötn, rising generally towards NE, and maximum depth ranges from a few m to 32 m (Rist 1975; Pálmarsson 2009). Most of the younger generation lakes are drained by Vatnakvísl and Fossvatnakvísl, except Hraunvötn which have no surface drainage.

Many of the lake-filled depressions have narrow pits in the bottom, most conspicuous in lakes within the secondary craters, and generally reaching down to 533-549 m a.s.l. as calculated from Rist (1975). This depth interval corresponds closely to the pre-eruption bottom elevations of 535-555 m a.s.l. obtained for this part of the basin by a different method (sections 5.2 & 5.5). The pits may define the interface between the pre-eruption strata and the 1477 CE volcanic products where explosive interaction between hot lava and water/wet-sediments took place.

The present passage of the Tungnaá river through the Veidivötn basin is a flat, winding channel, about 10 km long and 0.5-1 km wide, with a slope of <0.5 m/km. About 4 km lie within the Svartikrókur tephra rings. The crater floors have been levelled off, partly by debris from the failed tephra dams and partly by alluvials.

Groundwater level in the basin rose permanently after the massive infilling by the 1477 CE Veidivötn eruption as reflected by lake levels of up to 590 m a.s.l. in the Hraunvötn lakes in NE part of the basin (Fig. 12). Assuming that the lake levels of the Fiskivötn stage were between 560-565 m a.s.l. the rise was 25-30 m at the NE end and 5-10 m at the SW end of the Veidivötn basin, but negligible in the Irpuver pass.

The effects of the Veidvötn eruption on the groundwater flow at depth can only be hinted at. The substrata in the basin were subject to shallow-level (<100 m) coring by the explosive activity (Giniaux 2013), intrusion of a large near-continuous dyke, heating by the magma and substantial tectonic movements, all of which altered the permeabilty. The cored-out areas are filled by a mixture of fragmented volcanic material and alluvial/lacustrine sediments in varying proportions, and of varying permeability, except where the final phase was effusive. Below the cored-out areaa a solidified dyke is apprehended along the whole length of the basin, a near vertical wall with a width of metres and a depth of several km. The largest springs in the basin lie preferently along the trace of the dyke/fissure (Sigbjarnarson 1972, Adalsteinsson 1987). If the groundwater flow into the basin is mainly from the east (Sigbjarnarson et al 1976), the dyke could have some blocking effects, resulting in a higher groundwater level on its east side. This appears to be the case, according to Adalsteinsson (1987) but is not as obvious on the hydrological map by Hjartarson (1988).

The observable long term effects of the Veidivötn eruption on the surface hydrology can be summarized as follows: 1) the Fiskivötn lakes were reduced to five or six remnants along the edges of the Veidivötn basin; 2) a new generation of lakes developed in depressions within the 1477 CE volcanic products; 3) a new drainage system was established, including a new passage for Tungnaá/Jökulgilskvísl through the basin; 4) the groundwater reservoir was enlarged and groundwater level was raised at both ends of the basin, by 5-10 m at the SW end and 25-30 m at the NE end, but very little, if at all, in the Irpuver pass.

6. Discussion

The discussion will mainly focus on the duration of the stages and the recovery of the hydrology in the Veidivötn basin which was affected by the two younger eruptions. The effects of heavy tephra fall over the drainage basin of the Tungnaá river (Fig. 3) are not be assessed. Dam failures will be subject to another report. Effects of future eruptions are beyond the scope of this report.

6.1 Summary of changes

The conditions in the Veidivötn basin have changed during the last 2000 years from a single large lagoon during the Hnausalón stage to numerous and generally small lakes during the Veidivötn stage. The capacity of the basin to store water during unstable post-eruption stages diminished from ≥1 km^3 in a single reservoir during the Langalón stage, to ≤0.45 km^3 in four reservoirs during the Kýlingalón stage.

The bed of the Tungnaá river between Svartikambur and Irpuver has been subject to repeated changes since the Hnausalón stage about 2000 years ago. The Tungnaá river and its drainage basin received heavy tephra fall of up to 5 m in the 1477 CE eruption and up to 1 m in the 877 CE Vatnaöldur eruption (Fig. 3). Large lakes have existed in its bed, now emptied or filled in. Tungnaá is now a braided river along this stretch. The bed of the Tungnaá river downstream from the basin has not been significantly altered since the Langalón stage following the Vatnaöldur eruption in 877 CE and the emptying of Krókslón lake (Larsen 2019).

The groundwater reservoir in the Veidivotn basin changed as a result of the Veidivötn eruption, partly by massive infilling of volcanic material and partly by a dike running along the whole basin at depth.

6.2 Duration of the unstable stages

In the following discussion the focus is on the events in the Veidivötn basin. The recovery time from the effects of tephra fall on the surrounding terrain, i.e. on clogging of waterways, run-off during spring thaw, ablation of winter snow, is not considered here, nor the effects of heavy tephra fall on glaciers that can significantly retard ablation and run off (e.g. Driedger 1981; Adhikary et al. 2000; Kirkbride and Dugmore 2003; Dragosics et al. 2016; Möller et al. 2018). These factors should, however, be taken into account in future modelling of recovery times.

The Langalón stage lasted until the tephra dam had eroded down and Tungnaá flowed freely through the SW part of the basin. If Tungnaá had no glacial component in the 9th century, given the climate conditions, filling time may have greatly exceeded the ~140 days obtained by the present average discharge. The run-off and springfed components (Pálmarson 2009) could have filled the lake in ~200 days. The failure of the dam and emptying of the lake will be treated elsewhere (Gudmundsson and Larsen in prep). “Complete” emptying and establishment of a new drainage pattern in the area covered by Langalón may have taken years.

The Kýlingalón stage has a much more complex history. The preceding eruption took place within the basin and in addition to leaving complex formations that radically changed the basin topography, this eruption also affected the groundwater reservoir in the basin. Here it is postulated that the Kýlingalón stage lasted until 1) the groundwater reservoir had recharged and adjusted to the new conditions in the Veidivötn basin; 2) the water stored in the last unstable lakes had been disharged.

The duration of the Kýlingalón stage can be crudely approached using the following assumptions:

1) Recharge of the groundwater reservoir. Assuming that all the tephra, about 7.5 km^3 (compacted) or 2.5 km^3 DRE with mass of 6.75 x 10^{12} kg (Larsen et al. 2013, Larsen unpubl), was erupted within the Veidivötn basin, and assuming that water/magma mass ratio of 0.3 (Wohletz and Sheridan 1983) was needed to convert the magma into hydromagmatic tephra, about 2 km^3 of water could have been used in the process. Wohletz and Sheridan (1983) do not take vesiculation by gases in the magma into consideration, nor impurities in water from lakes or wet sediment that may enhance explosivity (White 1996; Wohletz 2002). Recent calculations based on water availability in the Grímsvötn 2011 eruption indicate lower ratio, 0.2-0.25 (Gudmundsson et al. 2014), that would reduce the water „consumption“ to ~1.4 km^3. Further assuming that the raise in groundwater level caused by the 1477 CE volcanic products in the basin, 0-25 m, affected an area of 270 km^2 (Vatnakvísl and Snjóöldukvísl drainage basin, Rist 1956) and could be represented by a cone with that base, with a medium of 60% porosity, about 1 km^3 of water would be needed to compensate for the enlarged reservoir. Alternatively, using 90 km^2 as the drainage basin (Aðalsteinsson 1987), about 0.5 km^3 would be needed. Water lost through evaporation during secondary explosions and after the eruption ceased is not considered. A total of 2-2.5 km^3 (2000-2500 GL) might have been required to recharge the groundwater reservoir after the Veidivötn eruption. The current average discharge of the streams draining the middle part of the Veidivötn basin is ~20 m^3/s (Pálmarson 2009), corresponding to 0.63 km^3/year (630 GL/year). This could recharge the groundwater reservoir in 3-4 years. The rivers Tungnaá and Jökulgilskvísl contributed to the recharge in the SW part of the Veidivötn basin. Keeping in mind uncertainties such as the effects of tephra deposition on runoff and melting, the recharge process is nevertheless likely to have lasted several more years.

2) Emptying of unstable lakes. Assuming that a channel past the dam formed by the Ljótipollur tephra slide in Kýlingalón had been eroded in 3-5 years (see 5.7), the disappearence of two unstable lakes in the drainage basin of Vatnakvísl, Nýjavatnslón and Skálavatnslón, would terminate the unstable period. They could not fill until the groundwater reservoir had recovered and may have lasted for some time afterwards.

Here it is found likely that recharge-and-adjustment of the groundwater reservoir determined the duration of the Kýlingalón stage, and that it was terminated by the (stepwise) emptying of Nýjavatnslón and Skálavatnslón. Duration of a decade for the unstable Kýlingalón stage is therefore considered realistic.

6.3 Hazards

The history of the lake system in the past 2000 years is characterized by stable periods lasting centuries and unstable stages lasting years to decades.

The greatest hazard posed by the tephra dammed lakes was that of large (possibly up to 2 km^3) floods with peak discharge in thousands of m^3/s. This aspect has however changed with the diminishing capacity of the basin to store water during unstable stages. An eruption damming the Irpuver pass to 580 m a.s.l. could create similar situation as during the Kýlingalón if no mitigation, such as controlled removal of unstable dams, was carried out.

In a future eruption within or at the margin of the Veidivötn basin, damming of the rivers would be mitigateable. In an explosive eruption with heavy tephra fall similar to the Veidivötn eruption other factors might, however, be unmitigateable. These could include: 1) delayed ablation of winter snow and run-off during spring thaw, 2) delayed ablation of glacier ice due to heavy tephra fall and 3) depletion of a ground water reservoir with a recovery time of years/decades.

7. Summary and conclusions

- Three eruptions have affected the hydrology of the Veidivötn basin and the Tungnaá basin upstream from the Irpuver pass in the past 2000 years.
- The history of the lake system during this time slice is characterized by stable periods lasting centuries and unstable stages lasting years to decades.
- Five "stages" can be recognized: the stable Hnausalón stage lasting about a millennium until the 877 CE Vatnaöldur eruption; the consequent unstable Langalón stage lasting years/decades; the stable Fiskivötn stage lasting ~600 years until the 1477 CE Veidivötn eruption; the consequent unstable Kýlingalón stage lasting decade(s); and the current stable Veidivötn stage that has lasted 530-540 years.
- The Tungnaá river, currently a major provider of hydropower, was dammed and its channel modified by tephra and/or lava of the three volcanic eruptions. During the unstable stages its flow was barred for months to years resulting in formation of large lakes with dishargable volumes of up to 1.9 km^3.
- Large (up to 140 km^2) unstable lakes were formed as a consequence of the two youngest eruptions in 877 CE and in 1477 CE and existed for years to decades.
- Failure of the Langalón tephra dam resulted in a large (5000-20000 m^3/sec) flood onto the lava fields downstream from Irpuver and along the Tungnaá riverbed. However, pervious lava fields apparently absorbed a great part of the water. Discharge in the Thjórsá river channel at Búrfell mountain never exceeded 10000 m^3/s.
- Emptying of unstable lakes during the Kýlingalón stage was complicated by multiple dams that also reduced the discharge of the largest floods to several thousands m^3/s.
- The Sigalda gorge was eroded into its present form and the old Krókslón lake emptied as a consequence of the Vatnaöldur eruption in 877 CE.
- A future explosive eruption within or at the margin of the Veidivötn basin could create conditions for unstable lake similar to Kýlingalón unless mitigated by e.g. dam removal. Another consequence of such an eruption could be depletion and reorganization of ground water reservoir with a recovery time of years to decades.

Final comment

This report only scratches the surface of the complex hydrological history of the Veidivötn basin and its vicinity. Much more work is needed to obtain sufficiently detailed data on this unique history.

Firstly, systematic work on the shorelines could yield information not only on the actual elevations of these shorelines and the associated lake levels but possibly also information on tectonic movements such as tilting and subsidence within the whole area or some parts of it. These shorelines provide an unique tiltmeter tens of km long and wide within a volcanically and tectonically active area. Furter work must include digging onto the bench of the shorelines (not possible without permit from the Ministry of the Environment) and establish absolute elevations through D-GPS.

Secondly, the effects of heavy tephra fall (thickness in meters) on a river basin need to be assessed and modelled, e.g. on clogging of waterways, on retarded ablation of winter snow and run-off during spring thaw, on negative/positive ablation and runoff from glaciers and on increased transport of sediments through a river system.

Acknowledgements

Most of the research on the tephra dammed lakes was carried out at the Nordic Volcanological Institute in the late 1980ies - early 1990ies, partly paid for by the National Power Company and by the National Energy Authority during the geological mapping project supervised by late geologist Elsa G. Vilmundardóttir. Her invaluable help in the field and elsewhere is greatly appreciated. Kristín Gísladóttir helped to design the original maps. Adalsteinn Eiríksson took some of the photographs and assisted in the field. Magnús T. Gudmundsson estimated peak flows when the tephra dams failed. Andrew Dugmore provided useful suggestions, Davíð Egilson and Jónas Guðnason critically read the manuscript. Topography relies mostly on the topographic maps of the National Director of Electricity, National Energy Authority and National Power Company in 1:20000 with 5 m contours. Overview of the research area is from Google Earth satellite images. Finally Loftmyndir ehf are thanked for allowing high-resolution aerial photographs on their web MAP.IS to be used to demonstrate complex features in the Veidivötn basin.

Íslenskt ágrip:

Gjóskustíflur og skammlíf vötn - þróun Veiðivatnasvæðis í 2000 ár.

Skammlíf vötn bak við stíflur úr gjalli, vikri og ösku verða til öðru hvoru á eldvirkum svæðum. Slíkar uppistöður geta myndast þar sem sprengigos eru ríkjandi eða stór þáttur eldvirkni á vatnasvæðum fallvatna. Það fer svo eftir stærð og staðsetningu þessara óstöðugu vatna hvort þau geta valdið tjóni á náttúrulegu og/eða manngerðu umhverfi þegar gjóskustíflurnar láta undan.

Sprungusveimur sem tilheyrir eldstöðvakerfi Bárðarbungu liggur til suðvesturs frá Vatnajökli inn í Torfajökulssvæðið (Mynd 1). Tungnaá, önnur stærsta áin á vatnasvæði Þjórsár, hefur runnið yfir SV-hluta sprungusveimsins síðan ísa leysti af landinu. Áin hefur verið hrakin úr farvegi sínum af mörgum eldgosum þar, yfirleitt af hraunrennsli en í yngstu gosunum af gjóskugígum og stíflum úr gjalli, vikri og ösku.

Stór skammlíf og óstöðug vötn mynduðust í farvegi Tungnaár eftir tvö yngstu gosin á SV-hluta sprungusveimsins. Vötnin skildu eftir strandlínur sem vitna um tilvist þeirra og marka vatnsborð. Bæði gosin, Vatnaöldugos 877 og Veiðivatnagos 1477, voru sprengigos að mestu vegna áhrifa vatns á basaltkvikuna. Ásamt flæðigosi fyrir um 2000 árum breyttu þessi tvö sprengigos landslagi og vatnsfarvegum á stóru svæði sem hér verður nefnt Veiðivatnadæld og nær frá Hraunvötnum í norðri að Landmannalaugum í suðri (Mynd 2). Til einföldunar er breytingum og þróun svæðisins skipt í fimm tímabil eða stig sem er lýst hverju fyrir sig.

Hnausalónsstig. Fyrir um 2000 árum opnaðist gossprunga við Hnausa sem þveraði farveg Tungnaár, einn gíganna er Hófurinn í Hófsvaði. Hraunið úr þessu gosi, Tjörvahraun THj, rann upp að móbergshæðum við Irpuver og hækkaði farveg Tungnaár um ~20 m (19 m í borholu TH-11 um 2,7 km neðar) og þar með grunnvatnsstöðu svæðisins. Þá varð til hraunstíflað vatn, hér nefnt Hnausalón, sem Tungnaá og Jökulgilskvísl hlóðu framburðarkeilu eða eyri út í. Þykktarkort af gjósku frá tveim yngstu gosunum eru til (Mynd 3) og með hjálp topografískra korta og dýptarkorta af Veiðivötnum með 5 m hæðarlínum er hægt er að „fjarlægja" gjóskuna úr dældinni. Þá kom í ljós að þetta vatn hlýtur að hafa náð alllangt inn eftir Veiðivatnadældinni (Mynd 4).

Ekki var tekið tillit til vatnsborinnar gjósku í dældinni eða höggunarhreyfinga í yngri gosum. Umfang Hnausalóns, hér miðað við hraunhaft í ~565 m y.s., kann því að hafa verið minna eða stærra en hér er sýnt, um 90 km^2 að meðtöldum vötnum í Kýlingum. Hækkuð grunnvatnsstaða og tilurð Hnausalóns höfðu áhrif á eldvirkni í Veiðivatnadældinni í næstu tveim gosum, þau voru freatómagmatísk sprengigos.

Langalónsstig. Vatnaöldugossprungan 877 opnaðist í jaðri Veiðivatnadældar og Hnausalóns. Sprengigosið hlóð upp vikur- og öskugígum og þykku gjóskulagi þvert yfir farveg Tungnaár og stíflaði útrennsli úr dældinni. Bak við gjóskubingina varð til lón sem teygði sig bæði upp eftir farvegi Tungnaár og inn eftir Veiðivatnadældinni (Mynd 6). Um 1 m af vatnshreyfðri gjósku bættist ofan á eyrina sem Tungnaá og Jökulgilskvísl höfðu myndað (Mynd 5). Á nokkrum stöðum eru strandlínur í um 580 m y.s. varðveittar þar sem yngri vatnagangur náði ekki til, t.d. í Tjörvafelli (Mynd 7ab) og utanvert á stærstu Vatnaöldugígunum (suðaustanmegin). Strandlína í Austurbjöllum í 582.5 m y.s. er grafin í Vatnaöldugjósku (hæðarmæling miðuð við grunn turns í Suðurlínu) en er þakin vatnsbornum vikri úr Veiðivatnagosi og gæti því tilheyrt yngra lóni. Óvíst er að vatnsborð Langalóns hafi nokkurn tímann orðið stöðugt en líklegt að það hafi verið milli 575 og 580 m y.s. þegar mest var. Fyllingatími lónsins (án jökulvatns) gæti hafa verið um 1 ár. Miðað við verstu sviðsmynd, vatnsborð í 580 m y.s. (Mynd 6), var flatarmál Langalóns um 140 km^2 og miðlunarrými niður í 560* m y.s. um 1,5 km^3. *(Gert er ráð fyrir að farvegur Tungnaár hafi rofist og lækkað þegar flæddi úr lóninu).

Gjóskustíflan var milli 2,5 og 3 km á lengd. Líklegt er að hún hafi rofnað strax og vatnaði yfir hana næst Hnausum þar sem hún var lægst. Líkanreikningar benda til mesta útrennslis á bilinu 5000-20000 m^3/sek eftir hversu hratt rofið var. Lónið gæti hafa tæmst að mestu í einu flóði. Hluti flóðsins rann um farveg Tungnaár til Krókslóns og gróf það út, hluti flæddi áfram vestur yfir gropin hraun þar sem erfitt er að rekja flóðset lengra en ~15 km frá upptökum. Vatnið hefur að lokum runnið áfram til Þjórsár. Engin merki um stórt flóð finnast meðfram Þjórsá, t.d. er jarðvegur með óhreyfðri loftborinni Vatnaöldugjósku á hrauni THf á Búrfellshálsi rétt ofan við Þjófafoss.

Fiskivatnastig. Eftir tæmingu Langalóns var áfram vatnasvæði í Veiðivatnadældinni. Nægt dýpi var á nokkrum stöðum með jöðrum hennar, miðað við að farvegur Tungnaár út úr dældinni væri í um 560 m y.s. (eins og nú neðan Irpuvers). Norðan til og um miðbik hennar voru vötn voru á a.m.k. fjórum stöðum en óljóst að hve miklu leyti grynningar og blautir setflákar skildu þau að (tillaga á Mynd 8). Suðvestantil í dældinni grófu Tungnaá og Jökulgilskvísl sér farvegi gegn um framburðarkeilu frá Hnausalóns- og Langalónsskeiðum. Þar voru einnig smærri vötn, t.d. forveri Frostastaðavatns.

Kýlingalónsskeið. Syðsti hluti gossprungunnar í Veiðivatnagosinu 1477 opnaðist eftir miðri, endilangri Veiðivatnadældinni. Gosið þar var sprengigos í fyrstu, sem hlóð upp víðum en fremur lágum gjóskugígum, en breyttist síðar í flæðigos á nokkrum stöðum. Stórir gjóskugígar hlóðust upp þvert yfir farveg Tungnaár og hluti af gígbarmi skreið niður í farveginn. Tvö lón mynduðust í farvegi Tungnaár og tvö önnur um miðbik dældarinnar (Mynd 9).

Stærsta lónið, Kýlingalón, var í farvegi Tungnaár og stóð uppi bak við tvær stíflur, gígbarm í 580 m y.s. úr þéttpakkaðri gjósku blandaðri seti, og lægri skriðu úr sambökuðu gjalli og ösku. Það var um 35 km^2 miðað við vatnsborð í 580 m y.s. Fyllingartími gæti hafa verið um 2 mánuðir. Kýlingalón tæmdist í nokkrum áföngum þegar stíflurnar tvær rofnuðu, sem má sjá á strandlínum í Kýlingum (Mynd 10cd). Önnur lón voru minni. Lónin um miðbik dældarinnar fylltust ekki (og tæmdust ekki) fyrr en grunnvatnsgeymir svæðisins hafði fyllst.

Veiðivatnaskeið. Eftir tæmingu allra lóna tók við nokkuð stöðugt tímabil sem enn stendur (Mynd 12). Veiðivötnin eins og við þekkjum þau eru af tvennu tagi jarðfræðilega séð. Langflest vötnin í Veiðivatnadældinni eru ung og fremur lítil og liggja innan í gígum eða eru umkringd gosefnum úr Veiðivatnagosi 1477 (dökkblá). Stærstu vötnin eru við jaðra dældarinnar og þau eru „leifar“ eldri vatna (ljósblá). Vatnsborð flestra vatna er hærra en áður vegna upphleðslu gosefna, nema e.t.v. að Snjóölduvatni undanskildu.

Gossprungur eru líklegar til að þvera farveg Tungnaár þegar næst gýs á suðvesturhluta sprungusveimsins. Ef gossprungur opnast í Veiðivatnadældinni er líklegt að í upphafi verði þar sprengigos sem hlaði upp allstórum gjóskugígum. Hæð gígbarma yfir fyrra umhverfi í yngsta gosinu var 40-130 m og mesta mælda þykkt gjóskulagsins utan gíga var 12 m í um 4 km fjarlægð frá gosopi. Upphleðsla gosefna í síðustu tveim gosum hefur takmarkað möguleikana á að safna vatni í stór óstöðug lón og með nútíma tækjakosti er hægt að koma í veg fyrir slíkt.

Langtímaáhrif sprengigosa af þessu tagi eru ekki metin hér. Basísk sprengigos byggja á samskiptum kviku og vatns. Þau ganga á vatnsforða aðliggjandi svæðis, bæði grunnvatn og yfirborðsvatn. Verulegt gjóskufall yfir vatnasvið fallvatna og leysingasvæði jökla getur haft áhrif á vatnabúskap, stíflað/tafið afrennsli, tafið snjóbráðnum, tafið bráðnun á leysingasvæðum jökla og valdið auknum setflutningi í ám og vötnum í töluverðan tíma eftir að atburðum lýkur.

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Table 2. Some points on the effects of the 1477 CE Veidivötn eruption on groundwater

Depletion of groundwater in the 1477 CE Veidivötn eruption:
- Tephra, 7.5 km^3, with bulk density of 0.9, weight 6.75 x 10^{12} kg.
- Water/magma mass ratio of 0.3, weight of water 2.0 x 10^{12} kg.
- Water/magma mass ratio of 0.2, weight of water 1.4 x 10^{12} kg.
- Water drawn from groundwater reservoir for tephra production: 1.4-2 km^3

Enlargement of groundwater reservoir due to accumulation of volcanic material:
- Maximum raise in groundwater level caused by the youngest eruption: ca 25 m.
- Area affected by raised groundwater level: 270 km^2.
- Volume calculated as cone, B = 270 km^2, h = 0.025 km, V = 2.25 km^3.
- Average porousity of media: 60%.
- Water required for adjustment: 1.3 km^3.
- Area affected by raised groundwater level: 90 km^2
- Water required for adjustment is 0.5 km^3.

Recovery time of groundvater reservoir:
- Volume of water needed to recharge groundwater reservoir: 2-2.8 km^3
- Rate of recharge 20 m^3/sec (discharge of Vatnakvísl) or 0.63 km^3/year.
- Time of recovery ≈ 3 - 4.5 years.

Drainage areas affected by the 1477 CE Veidivötn eruption:
- Tungnaá + Jökulgilskvísl + Vatnakvísl: 1440 km^2 (Rist 1956)
- Tungnaá below glacier: 121 km^2 (Björnsson 1982)

Possible deposition rates of Veidivötn tephra:
- 5 m of tephra in 48 hours ≈ 0.003 cm/sec ≈ 0.18 cm/min ≈ 10.8 cm/hour
- 5 m of tephra in 24 hours ≈ 0.006 cm/sec ≈ 0.36 cm/min ≈ 21.6 cm/hour
- 5 m of tephra in 12 hours ≈ 0.012 cm/sec ≈ 0.72 cm/min ≈ 43.2 cm/hour
- Comparable deposition rate of H-1980 tephra:
- 0.35 m of tephra in 2 hours ≈ 0.005 cm/sec ≈ 0.3 cm/min ≈ 18.0 cm/hour

Table 3. Summary of changes, Veidivötn basin:

Topography : Major topographic changes, mostly permanent.
- Major permanent changes of relief, mostly positive.
- Minor temporary changes of relief (modified shortly after the eruption).

Hydrology : Major hydrologic changes, temporary and permanent.
- Temporary changes of drainage, damming of Tungnaá passage.
- Permanent changes of drainage of Vatnakvísl, alteration of the course of Tungnaá, Vatnakvísl.
- Permanent raise of groundwater level, in particular middle and NE part of basin.
- Temporary changes of lake system, formation of unstable lakes.
- Permanent changes of lake system, establishment of a new stable lakes.

Discharge : Major temporary changes, no known permanent changes.
- Temporary shortage of groundwater during recharge of reservoir, due to increased capacity (result of accumulation of volcanic material) and depletion (result of explosive interaction with magma).
- Permanent changes of groundwater flow may have resulted from changed permeability of substrata.

Table 4. Summary of changes, Tungnaá drainage basin (upstream from Veidivötn basin):

Topography : Minor changes of topography, mostly confined to the river beds.
- Permanent raising of the bed of Tungnaá upstream from Kýlingar.
- Permanent raising of the bed of Jökulgilskvísl.

Hydrology : Minor hydrologic changes
- Permanent filling in of Stórisjór lake (in the riverbed).

Discharge : Major short term effects, no long term effects.
- Temporary clogging of Tungnaá bed and some tributaries.
- Temporary changes in glacial ablation/run-off factor, caused by tephra cover on the glacier
- Temporary changes in spring and summer run-off, tephra cover on last winters snow
- No permanent effects on the discharge of Tungnaá.
- Minor temporary effects on discharge (damming) of Jökulgilskvísl.
- No permanent effects on the discharge of Jökulgilskvísl.

Appendix 1 - 6 to RH 05-2023

Tephra dammed lakes in the Veidivötn area, Iceland

Supporting material - photographs, aerial photos, drawings, texts

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Institute of Earth Sciences
University of Iceland

Looking NE along the Tungnaá river flowing within the 1477 CE Svartikrókur tephra rings and the former Snjóöldulón, now filled by alluvium of Jökulgilskvísl and Tungnaá rivers.

1. Changes from Hnausalón stage to Kýlingalón stage, SW Veidivötn basin

The SW part of the Veidivötn basin is a key area for understanding the changes of the last 2000 years. Deposition of alluvium and tephra during periods of high lake levels in this area and erosion of these deposits when the lakes disappeared/emptied is explained below.

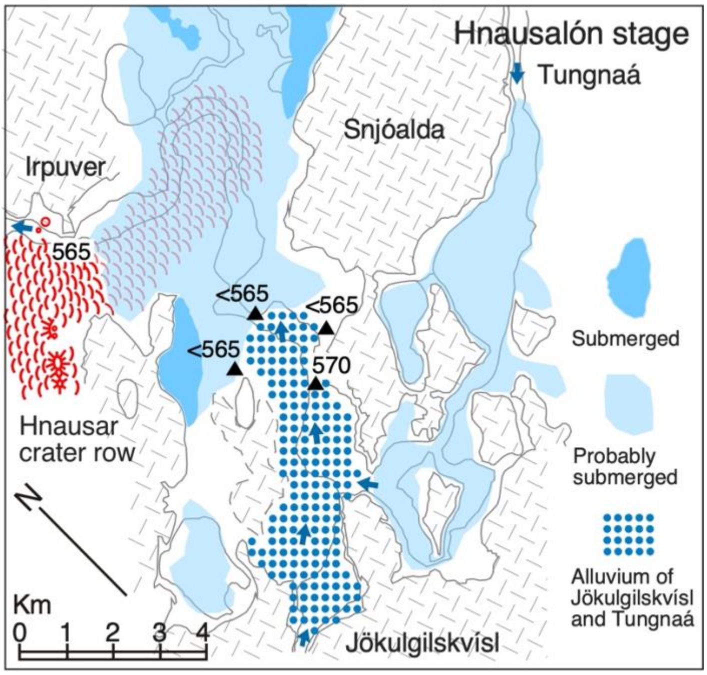

Figure 1-1. The situation in the SW end of the Veidivötn basin during the Hnausalón stage towards the end of that stage in the 9th century. Alluvial material, mostly gravel from the Jökulgilskvísl river, had accumulated to ~ 570 m a.s.l. in the river channel, most likely forming a delta extending into lake Hnausalón. Cf section through the alluvium below (Figs 1-5, 1-6, and Figure 5 main text). The extent of Tjörvahraun THj is based on field observations, including identification of lava blocks in the ejecta of two craters of 1477 CE Veidivötn eruption (compare to the crater row in Fig. 1-4).

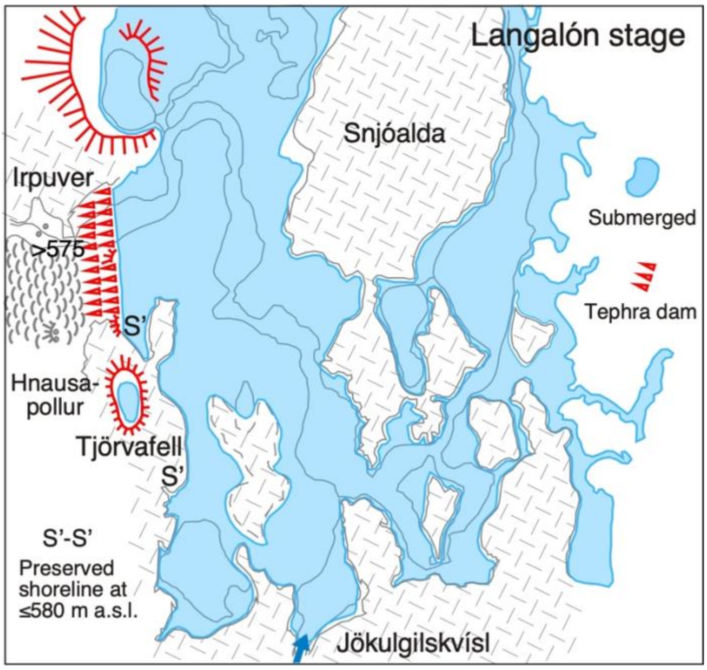

Figure 1-2. During the Langalón stage in the 9th century both tephra from the Vatnaöldur eruption and gravel from the Jökulgilskvísl were deposited on top of the Hnausalón alluvial deposit, see section through the alluvium below in Figs. 1-5 and 1-6.

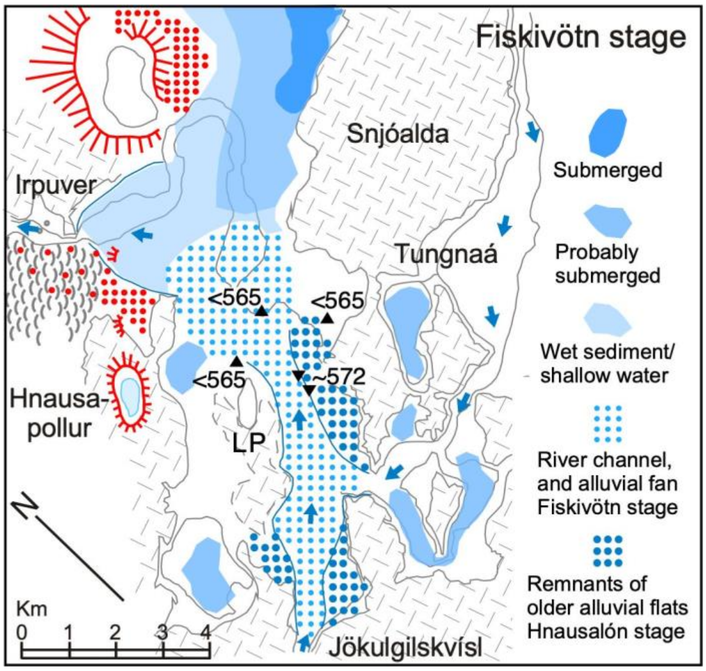

Figure 1-3. The situation in the SW end of the Veidivötn basin during the Fiskivötn stage (after the empying of Langalón in the 9th century until 1477 CE). A river channel was eroded through the alluvial sediments accumulated during the Hnausalón and Langalón stages, leaving a terrace on the right side of the channel. Black triangles at ~572 m a.s.l. indicate locations where terrace remnants are still visible, see Figs. 1-5 and 1-6 below. LP indicates where Ljótipollur explosion crater formed in the following eruption.

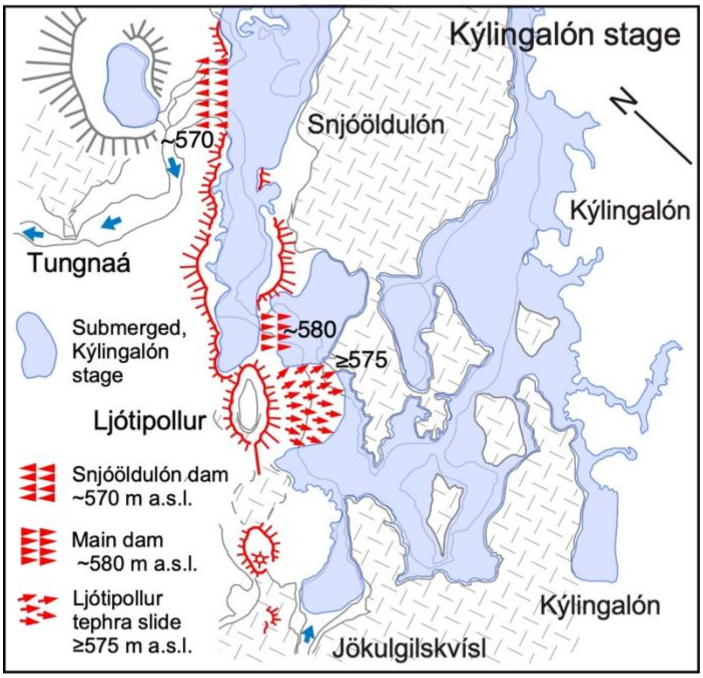

Figure 1-4. The situation shortly after the Veidivötn eruption in 1477 CE. The volcanic fissure opened partly through the alluvium, forming tephra rings and the explosion crater Ljótipollur. Towards the end of the eruption the SE flank of Ljótipollur failed and slid into the river channel, forming a 1.5 km long plug of tephra (spatter, ash and scoria at various stages of fusion and consolidation).

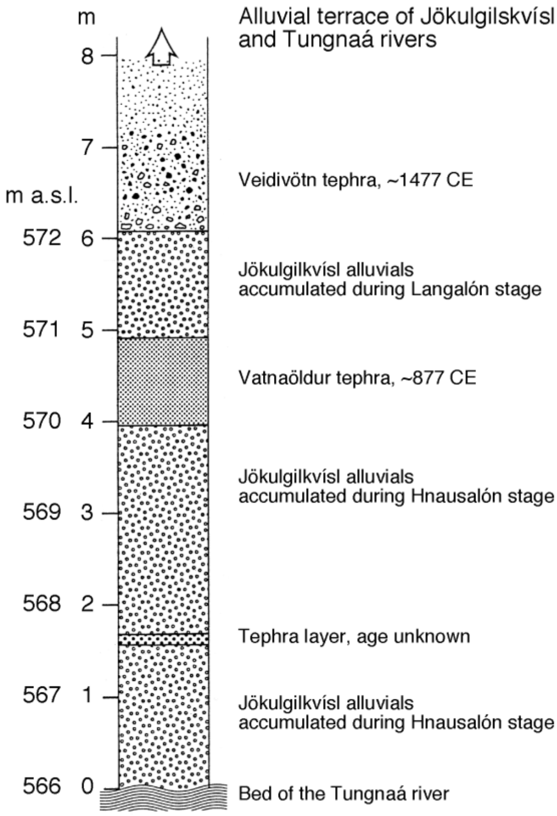

Figure 1-5. A section through the terrace. The gravel (large dots) was deposited by the Jökulgilskvísl river. Tephra from the 877 CE Vatnaöldur eruption separates the alluvium into gravel deposited during the Hnausalón stage (up to ~570 masl) and gravel from Langalón stage (up to ~572 masl). The base of the Ljótipollur tephra slide at top (here termed Veidivötn tephra). Location on Figures 1-1 (black triangle 570) and 1-3 (black triangle 572). "Bottom" at 566 m a.s.l. was estimated from NEA/NPC maps 3334&3439. (On MAP.IS from 2023 point 566 in the Tungnaá bed lies ~0.3 km downstream).

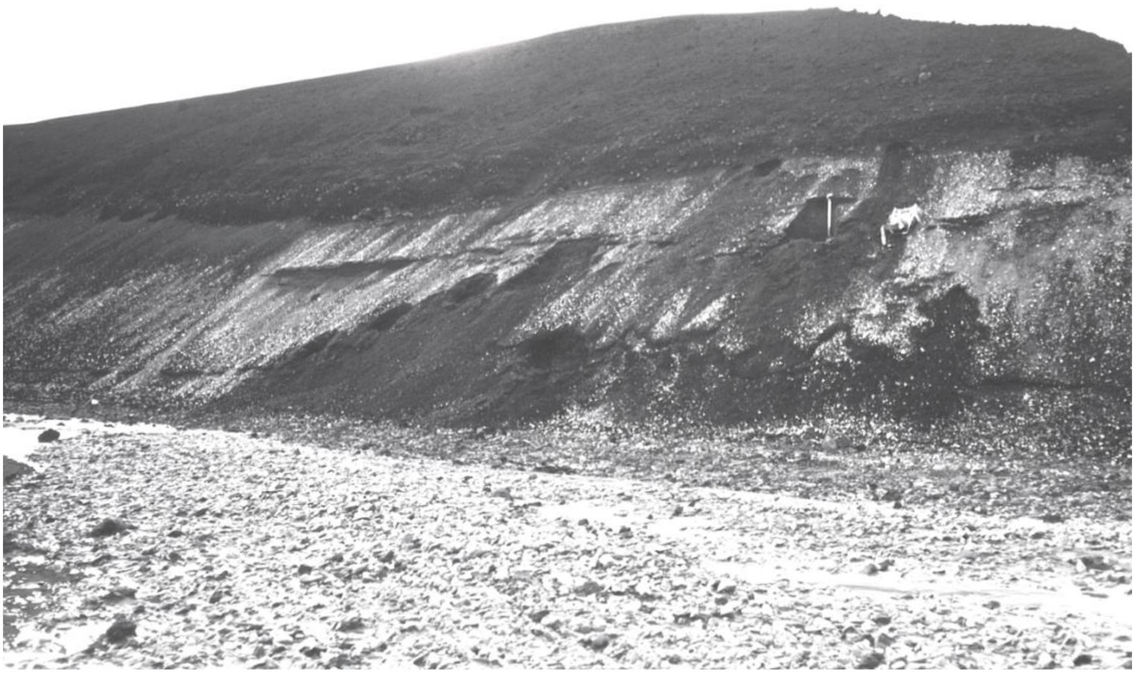

Figure 1-6. A section through the terrace (now covered by a scree) logged in 1982, the black & white photo taken at that time. 1 m shovel is standing in the cleaned section through the Vatnaöldur tephra.

2. Erosional scars in crater flanks formed during emptying of Langalón and Snjóöldulón/Kýlingalón

These three unstable lakes all emptied through and modified the river channel of Tungnaá. The tephra dams were flanks of craters built by bedded tephra ranging from basaltic hydromagmatic pumice and ash to scoria and spatter with a range of grain sizes, lithic material and compaction. Erosional scars left by the floods resulting from the dam failures are still visible and river Tungnaá, now flowing in the youngest flood channel, keeps some of the exposures into the crater flanks near-vertical.

The scars left by the 877 CE and 1477 CE floods in the flank of the largest Vatnaöldur crater are described together below. The tephra in the exposed scars is also briefly described.

Figure 2-1. Aerial photograph from MAP.IS/Loftmyndir ehf, showing the south rim and flank of the largest Vatnaöldur crater, lake Skyggnisvatn and the Tungnaá river. The 877 CE Vatnaöldur tephra is light grey and is partly mantled by dark grey air fall tephra from the 1477 CE Veidivötn eruption, originating from the Svartikrókur crater row (remnants of crater rims in lower part of figure).

The erosional channel/scar into the Vatnaöldur flank, left by the emptying of Langalón, is indicated by red arrow (at that time thick Vatnaöldur tephra deposits extended into the area now occupied by the Svartikrókur craters). The dark grey Veiðivötn tephra was deposited and draped over this scar, see also Fig. 2-2. The Veidivötn tephra was in turn eroded and overrun during the emtying of Snjóöldulón-Kýlingalón temporary lakes leaving scars indicated by yellow arrows, see also Fig. 2-2 and 2-3.

The large erosional scar or bank along the Tungnaá river (white arrow) was probably mostly eroded during the emptying of Snjóöldulón-Kýlingalón and consequently modified - and kept open - by the river, see also Figs. 2-5 and 2-6. North is up. Scale is in lower left corner.

Figure 2-2. Thick deposit of 1477 CE Veidivötn tephra in the flood channel/scar on Fig. 2-1. Photo taken near the lower yellow arrow on Fig. 2-1. To the right of the shovel (1 m) is massive primary airfall of bedded lapilli, bombs and ash with lithics of rhyolite gravel and basalt fragments. To the left of the shovel the Veidivötn air fall tephra has been eroded and on top of it lies irregularly bedded, water transported lapilli and ash filling shallow channels, presumably deposited during the emptying of Snjóöldulón-Kýlingalón lakes. To the far right the Veidivötn airfall tephra drapes over the scarp in the Vatnaöldur crater flank (red arrow on Fig. 2-1, close-up on Fig. 2-3).

Figure 2-3. Close-up of the flood channel/scarp eroded into the Vatnaöldur crater flank. Photo taken to the right of the red arrow on Fig. 2-1. The trunkated, bedded Vatnaöldur tephra (2 m scale) at the scarp is first overlain by wind and water redeposited Vatnaöldur tephra. Massive deposit of bedded Veidivötn airfall tephra (bombs, lapilli, ash and rhyolitic lithics) overlies the Vatnaöldur tephra, draping over the scarp, and is in turn overlain by redeposited, thinly bedded Veidivötn tephra. Close-up of the Vatnaöldur tephra is on Fig. 2-4.

Figure 2-4. Close-up of the lowermost exposed tephra in the Vatnaöldur crater flank. Massive, compact lapilli and bomb deposit with sparse basaltic lithics (completely without rhyolitic lithics), are interpreted as airfall. Thin ash-rich layers could be surge deposits. The tephra dam of Langalón lake consisted of this material.

Figure 2-5. A view towards NE along the erosional scar cut into the Vatnaöldur crater flank during the emptying of Snjóöldulón-Kýlingalón lakes, now the river-bank of Tungnaá, white arrow on Fig. 2-1. The thick, massive, lowest beds continue as far as seen (forming near-vertical wall) overlain by thinner airfall and surge beds. Person for scale is 1.7 m. Photo Magnús T. Guðmundsson.

Figure 2-6. Bedded, 15-20 m compacted tephra in the Vatnaöldur crater flank seen from NE across Tungnaá and Ósinn, the outlet of Lake Skyggnisvatn.

3. Shorelines/watermarks exclusively from Langalón lake

The Langalón temporary lake formed as a consequence of the 877 CE Vatnaöldur eruption. Shorelines of the Langalón lake are only preserved in certain areas because the eruption products of the 1477 CE Veidivötn eruption cover some of the areas and the temporary lakes forming after the Veidivötn eruption occupied some of the same basins. Below some examples of shorelines that unequivocally belong to Langalón and confirm its extent are shown.

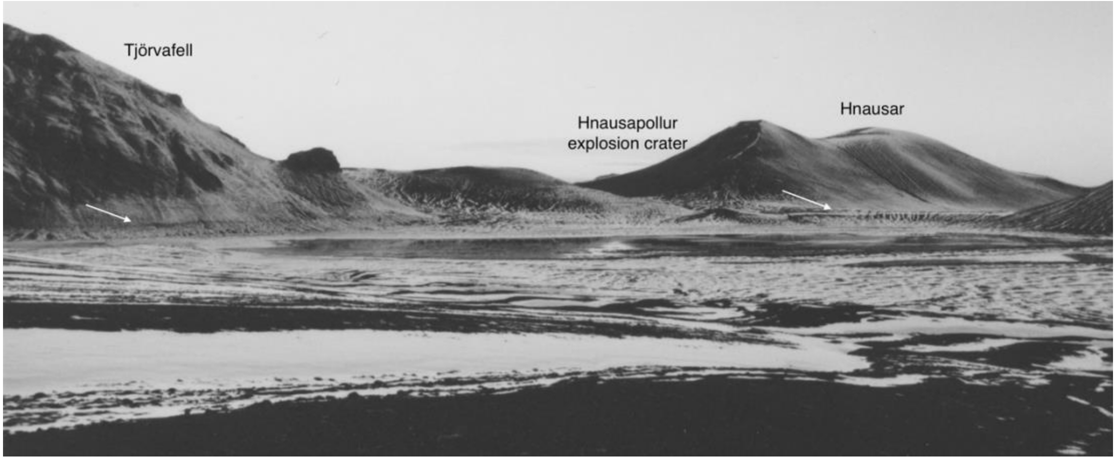

Figure 3-1. View towards Tjörvafell (left), Hnausapollur explosion crater and Hnausar hyaloclastite hill (right) looking north. Photo taken in late autumn with first snows showing details invisible at other times such as a shallow shoreline on a low isthmus (white arrow) in continuation of the Tjörvafell shoreline. Corresponding shoreline is detectable on the other side of the isthmus.

The small seasonal lake in the foreground (partly frozen) has a "spill-over" at ~575 m a.s.l. The possibility of a temporary lake forming there after the 1477 CE Veidivötn eruption is not supported. Matching shorelines at 580 m a.s.l. on the crater flanks of the Veidivötn eruption (Ljótipollur, Svartikrókur craters) would then be expected - where no such lines are found.

Figure 3-2. Aerial photograph from MAP.IS Loftmyndir ehf. Four small cones of basaltic tephra belonging to the 877 CE Vatnaöldur eruption lie on the lower slope of Hnausar hill. They constitute the southern end of the tephra dam holding up the Langalón lake. The two northernmost cones are partly washed away. The third cone, lying between 575 and 580 m a.s.l. mostly retains its shape although its flanks are eroded. Of the fourth and southernmost cone only small part of a rim remains. North is up.

Figure 3-3. Aerial photograph from MAP.IS/Loftmyndir ehf. Three large tephra rings in the 877 CE Vatnaöldur fremri crater row (white arrows point to NW rims) lie at the margin of the Veidivötn basin with the somewhat deformed SE rims built into the basin. The two larger tephra rings are eroded and tectonic fault cuts one of the rims. Darker coat of tephra from the 1477 CE Veidivötn eruption overlies the flanks. A step is cut into the SE flanks (red arrows) slightly above 580 m a.s.l. Below the step is a cover of slope-wash and remobilised tephra (lighter in colour). The step may mark the highest water level of Langalón lake. Tectonic fault cannot be excluded but no continuation of such fault has been found.

4. Kýlingalón and the Ljótipollur tephra slide

Shortly before the Veidivötn 1477 CE explosive eruption ended the SE flank of the Ljótipollur explosion crater failed and slid into the riverbed of Tungnaá. The evidence for this complex situation and its consequences is explained below by Figures 4-1 to 4-5.

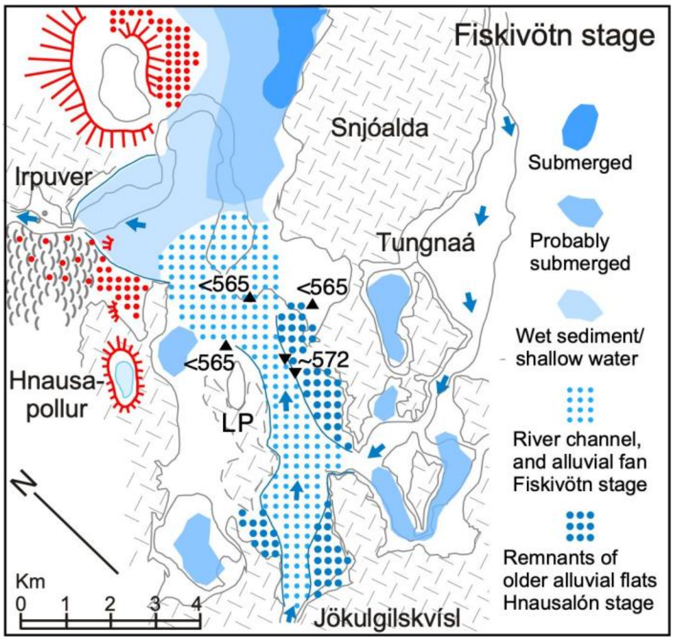

Figure 4-1. The situation in the SW end of the Veidivötn basin during the Fiskivötn stage (after the empying of Langalón in the 9th century until 1477 CE). A river channel was eroded through the alluvial sediments accumulated during the Hnausalón and Langalón stages, leaving a terrace on the right side of the channel. Black triangles at ~572m a.s.l. indicate locations where terrace remnants are still visible. LP indicates where Ljótipollur explosion crater formed in the following eruption.

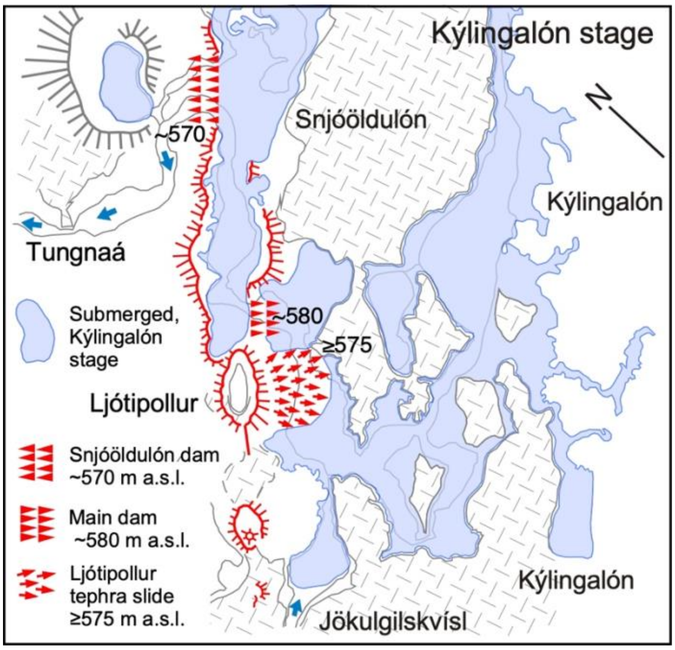

Figure 4-2. The situation shortly after the Veidivötn eruption in 1477 CE. The volcanic fissure opened partly up through the alluvial fan deposited during the Fiskivötn stage, forming interlocking tephra rings and the explosion crater Ljótipollur. Towards the end of the eruption the SE flank of Ljótipollur failed and slid into the river channel, forming a 1.5 km long plug of tephra (spatter, ash and scoria at various stages of fusion and consolidation). Tephra slide is the preferred term (over pyroclastic slide).

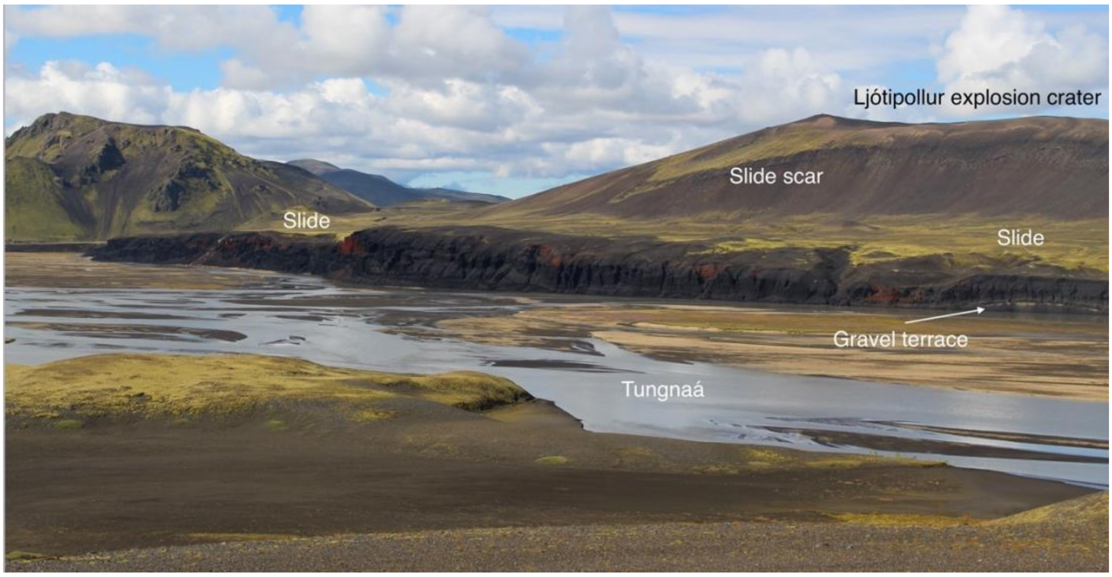

Figure 4-3. The failure scar (dark, steeply sloping) in the SE flank of Ljótipollur explosion crater and the tephra slide (flat, vegetated area below the scar) in a former bed of the Tungnaá river. The near-vertical, black and red wall eroded into the slide exposes indurated and sometimes agglutinated, bedded, black scoria, ash and spatter. The hot material was locally oxidized red, and spatter beds deformed after coming to rest. The pale alluvium in the present riverbed are rhyolite gravel and sand. Remnant of a former higher lying alluvial flat/gravel terrace lies below the slide at the far right (arrow), see following Figures for details.

Figure 4-4. Close-up of the middle part of the slide showing the bedding and the buried gravel terrace. The exposure farthest to the left is the same as on Figure 2-1. The alluvium in the largest exposure is at least 6 m thick and consists of pale rhyolite gravel, sand and silt. Farthest to the right is a gully cut into the slide where the alluvium can be viewed from another angle, see Fig. 4-6.

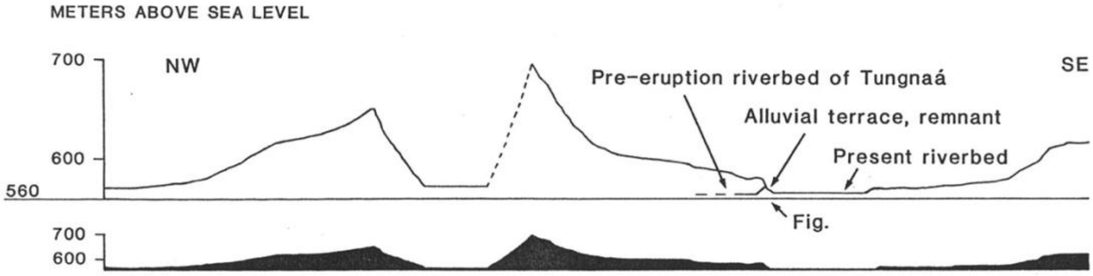

Figure 4-5. Cross section (4 km long) of the Ljótipollur explosion crater, the tephra slide (or pyroclastic slide) and surroundings. Elevations in upper panel are exaggerated (x4) to show the terrace remnant below the slide. The slide scar is more pronounced on the lower panel (h = l).

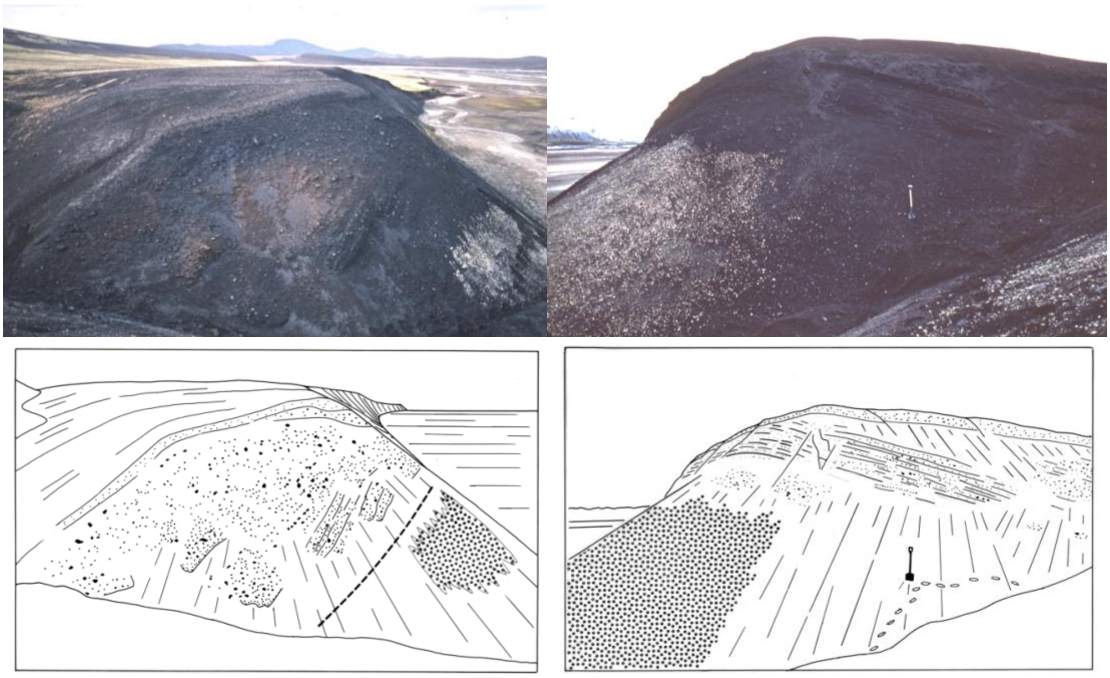

Figure 4-6. Photographs and drawings from both sides of the gully on Fig. 2-2, demonstrating that the alluvium slopes inwards (towards the slide), and that the lowest layers of the slide are collateral to that slope. Hence the tephra slide banked against an alluvial terrace. This was the east bank of a shallow channel that Tungnaá had cut into older alluvial flats during the Fiskivötn stage.

Left panels: Photograph and drawing looking towards NE, main body of the slide is towards left. A broken line indicates the boundary between the whitish gravel (dots) and the overlying, tilted scoria beds. The boundary was dug out after the photo was taken.

Right panels: Photograph and drawing looking towards SW, main body of the slide is towards right. A showel (~1 m) for scale. Note the inward dipping lower layers where the slide came to rest against the terrace.

The tilted scoria beds in these exposures, together with other terrace exposures and the topography of the tephra slide, demonstrate that the slide filled a former channel of Tungnaá river and was halted by gravel terraces. The terraces were mostly eroded away when the river dug a new channel (the present channel) past the slide. Where exposed the terrace surface was at approximately 572 m a.s.l. (see also Fig. 5 in the main text).

5. Shorelines of the Kýlingalón lake, including possibly rejuvenated Langalón stage shorelines.

The Kýlingalón temporary lake formed after the 1477 CE Veidivötn eruption. This lake occupied the same basin along the Tungnaá river as the SE part of the Langalón lake. The Kýlingalón lake was lowered in several steps due to multiple damming whereas the Langalón lake is assumed to have emptied in one event. Therefore, the highest shoreline in the Tungnaá basin upstream from Ljótipollur may belong to either lake or be juvenated by the younger lake. However, shorelines or watermarks in deposits from the 1477 CE eruption can only belong to the Kýlingalón stage, as seen on Fig. 5-1. Figs. 5-2 to 5-4 show potential rejuvenated shorelines.

Figure 5-1. Shorelines on the S slope of 1477 CE Ljótipollur explosion crater, upstream of the tephra slide that formed a second dam across Tungnaá river. At least two lines are discernable. The notch of the upper line lies at or above the 580 m a.s.l. contour (can also be observed on MAP.IS with 20 contour lines). They record at least two steps in the emptying of the Kýlingalón lake.

Figure 5-2. Three steps or shorelines are preserved on a slope at Stóri Kýlingur (left) in the narrows between the hill and the Kirkjufell mountain (right). The lowermost step is indistinct (level slightly above the car at far right). Shovel ~1m standing on upper most step (white cirle). Only one shoreline is preserved on the scree-covered slopes of Kirkjufell. A shallow pit was dug into the middle shoreline in early summer 1981. The upper part of the section was soil with a few dark tephra layers. At about 20-30 cm depth a 6-8 cm thick, irregularly bedded, basaltic tephra was found. It had the grain characteristics of the 1477 CE Veidivötn tephra including small rhyolitic lithics and was interpreted as reworked remnants of that tephra. A layer of soil separated this tephra from a washed, irregularly bedded basaltic tephra. Some of the beds were crystal-rich with the grain characteristics of the 877 CE Vatnaöldur tephra. Frosen ground prevented further digging. The area lies within The Fjallabak Natural Reserve and has not been re-surveyed.

Figure 5-3. Shoreline at ~580 m a.s.l at Litla Austurbjallavatn, marked by better preservation of vegetation. This shoreline is, at least in some places, cut into “washed” Vatnaöldur tephra indicating that Langalón lake formed the shoreline. It is, however, overlain by water carried Veidivötn lapilli. The area lies within The Fjallabak Natural Reserve. The shoreline was dug out and the bench surveyed to 582.5 m a.s.l. during the building of the Sudurlína transmission line in 1982.

Figure 5-4. Shorelines at Litli Kýlingur, the uppermost line most distinct. Kjartansson (1959) described shorelines in the Kýlingar area where the (uppermost) shoreline was found to be 12 m above the river in summer 1959. The river is close to 570 m a.s.l. at Litli Kýlingur. The shorelines have not been inspected as they are on the other side of Tungnaá river. The area lies within The Fjallabak Natural Reserve.

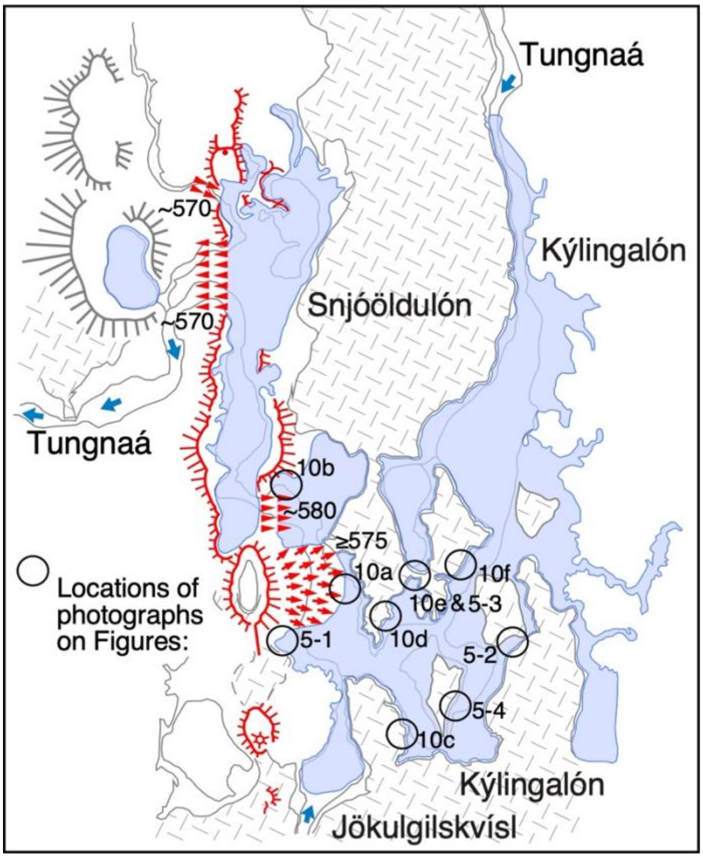

Figure 5-5. Location of photographs in Section 5.7, The Kýlingalón stage, and photographs in Fig. 5-1, 5-2, 5-3, 5-4. Note that Figures 10e and 5-3 show the same locality at different times.

6. Shorelines and extent of Snjóöldulón, Skálavatnslón and Nýjavatnslón lakes

During the Kýlingalón stage three small temporary lakes formed within the Veidivötn basin. Snjóöldulón was the largest and probably emptied when it was flooded from Kýlingalón. The other two, Nýjavatnslón and Skálavatnslón lay farther north in the basin. North is up unless otherwisely stated or marked. Figures 6-3 and 6-4 have been rotated 45° towards left.

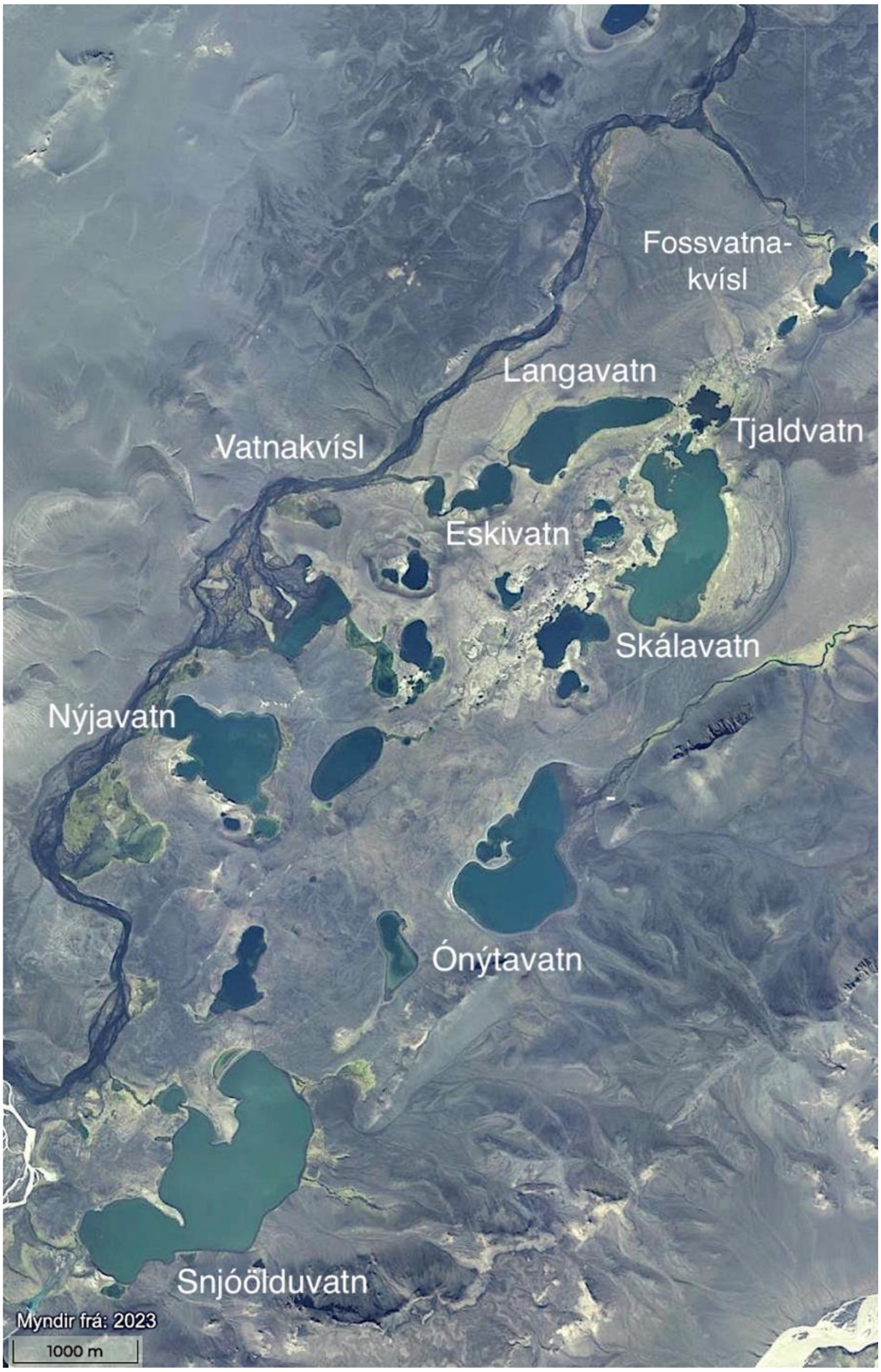

Figure 6-1. Aerial photograph from MAP.IS Loftmyndir ehf. Overview of the central part of the Veidivötn basin with names of relevant lakes and rivers. Scale in lower left corner. (Colour of aerial photo slightly changed).

Figure 6-2. Aerial photograph from MAP.IS Loftmyndir ehf. SW part of the present Snjóölduvatn and its original outlet. White arrow points to a scarp formed during the highest water level. Two channels were formed during the emptying with remnants of a crater flank (red arrow) in between. Aerial photo from 2013.

Figure 6-3. Aerial photograph from MAP.IS Loftmyndir ehf. Transparent blue overlay indicates the potential temporary extent of Snjóöldulón inferred from sporadic shorelines and scarps and the present topography and elevation.

The barriers are shown in red.

This reconstruction is an approximation and for clarification of potential post-eruption situation.

Figure 6-4. Aerial photograph from MAP.IS Loftmyndir ehf. Transparent blue overlay indicates the potential temporary extent of Skálavatnslón and of Nýjavatnslón farther downstream, based on shorelines (see Figs. below) and the present topography and elevation.

The most likely barriers are shown in red.

This reconstruction is an approximation and for clarification of potential post-eruption situation.

The temporary Skálavatnslón covered the present Skálavatn, Langavatn and several other lakes as well as parts of the rivers Vatnakvísl and Fossvatnakvísl. Around Skálavatn and Langavatn 2-3 shorelines can be discerned (Figs. 6-4 to 6-6) as well as “washed” horizons on the tephra flats around the rivers, here termed “bathtub marks” (Figs. 6-7 and 6-8).

Figure 6-5. Photograph looking westwards across lake Skálavatn towards lake Langavatn. A distinct shoreline is seen (halfway up) in the crater rim that forms the far bank of Langavatn. A lava bench of former lava lake lies below the shoreline.

Figure 6-6. Aerial photograph from MAP.IS Loftmyndir ehf. showing the south end of lake Langavatn, the narrow outlet and part of adjacent lake Eskivatn (left). A well-developed shoreline is evident at the south end of Langavatn.

Figure 6-7. Aerial photograph from MAP.IS Loftmyndir ehf showing two shorelines dug into the tephra in a crater rim at the north end of Skálavatn (arrows). The distinct line or step below the shorelines is a lava bench formed by a former lava lake within the tephra ring.

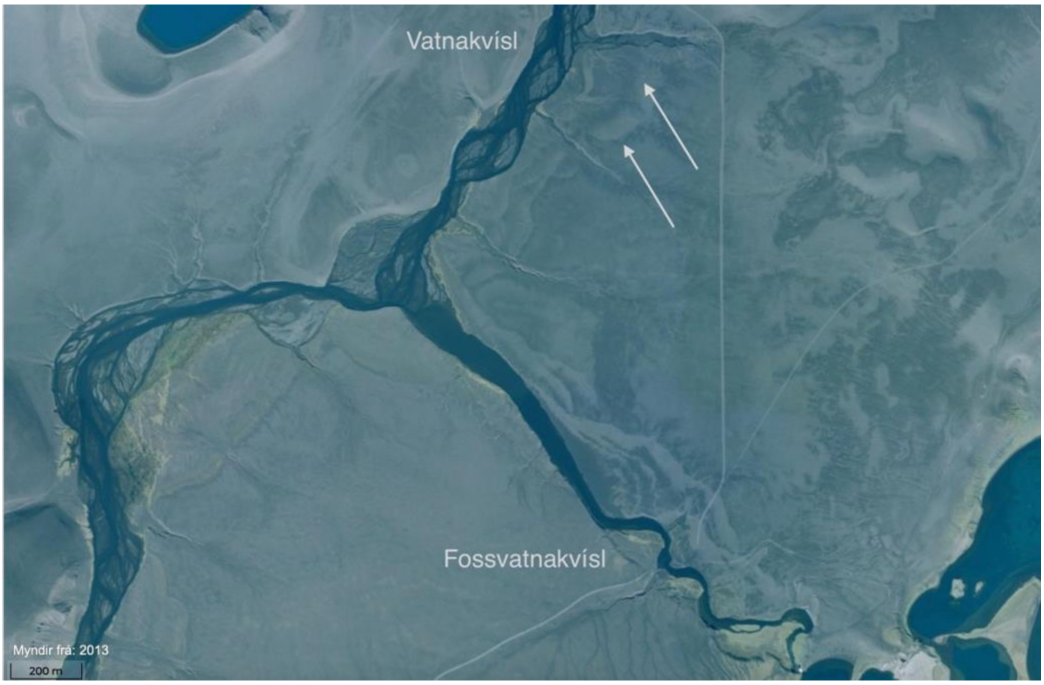

Figure 6-8. Aerial photograph from MAP.IS Loftmyndir ehf, showing the confluence of Vatnakvísl and Fossvatnakvísl rivers (overview on Figure 6-10). Arrows indicate “bathtub marks” on the tephra flats along Vatnakvísl. Note how the bathtub marks grade into eroded shorelines or steps along Fossvatnakvísl.

Figure 6-9. Aerial photograph from MAP.IS Loftmyndir ehf. Close-up of the bank of Vatnakvísl river, with 2-3 steps in the east bank, showing water level of lake Skálavatnslón during stepwise emptying.

Figure 6-10. Aerial photograph from MAP.IS Loftmyndir ehf. The temporary Nýjavatnslón left indistinct watermarks such as washed surfaces (white arrows). Note the smoother „texture“ of the two low areas compared to the texture higher on the slope. Aerial photo from 2013.